EXAMINATION OF SHIPBOARD MEASUREMENTS OF THE VERTICAL PROFILES OF MEAN TEMPERATURE, HUMIDITY AND WIND SPEED

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THESIS

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the Vertical Profiles of Mean Temperature,
Humidity and Wind Speed

by

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March 1974

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Examination of Shipboard Measurements of the Vertical Profiles of Mean Temperature, Humidity and Wind Speed

by

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Submitted in partial fulfillment of the requirements for the degree of

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ABSTRACT

The suitability of shipboard profile measurements of mean temperature, mean humidity and mean wind over the open ocean is examined on the basis of six hours and 20 minutes of simultaneous profile measurements made from the R/V Acania on 20-21 September 1973 near San Nicolas Island, California. Comparisons of the profiles obtained from the shipboard measurements, as well as the meteorological parameters derived from those profiles are made with results obtained from more stable platforms. Parameters examined include the Richardson number, the friction velocity, the drag coefficient and the roughness length.

The drag coefficient and roughness length were found to be generally larger than those obtained from more stable platforms, but the Richardson number and the relationships between the various parameters, as well as the profiles of wind speed and temperature themselves, compare favorably. The results indicate that a ship can be a suitable platform for measuring profiles.

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I. INTRODUCTION

There exists the need in many applied problems facing the Navy to obtain descriptions of the turbulent and mean structure of the atmospheric boundary layer over ocean waves. One such problem is that of describing the over-water regime with respect to the turbulent transfer of momentum and heat. Such information is needed for predicting changes in the thermal structure and other conditions in the upper part of the ocean. Other problems include the prediction of environmental conditions affecting optical wave propagation. Practical applications of importance to the Navy in the latter area have been summarized by Stehling (1973). Unfortunately, stable over-water platforms from which the required measurements can be made are very expensive to construct and, even if they could be built, most problems require observations at several locations.

One method for obtaining the required descriptions at the various specified locations would be to make shipboard measurements. Arguments against such measurements could be voiced by micrometeorologists who would be justifiably concerned about the influence due to the ship's superstructure and ship's motion. However, recent results by Denman and Miyake (1973) indicate that shipboard measurements do yield reasonable estimates of the boundary fluxes of momentum and heat. There remains the need for more results to verify their findings and evaluate the general utility of shipboard measurements. Such measurements should be of both profile and fluctuation properties.

This study is an examination of shipboard measurements of mean temperature, humidity and wind speed data at several heights. The instrumentation, measurement procedures, and a ship's suitability for open ocean micrometeorological observations will be evaluated on the basis of 40 observation periods on two days. Meteorological parameters examined are the Richardson number (Ri), the roughness parameter (Z_o), the drag coefficient (C_D), and the momentum transfer (u_*^2). The measurements of the mean temperature, mean humidity and mean wind speed will be evaluated by comparing the profiles of mean virtual potential temperature and mean wind speed with previous results from stable platforms over the sea. The derived parameters (Ri, C_D, Z_o and u_*) will be compared with published results for evaluation of the shipboard profile method for estimating boundary fluxes.

Calibration procedures, results, instrumentation, mounting procedures, and positions of the R/V Acania during observations will be described in detail.

II. BACKGROUND

The primary objective of profile measurements is to estimate, indirectly, the vertical fluxes of momentum, sensible heat and latent heat. The fluxes can be estimated on the basis of the profiles, or mean vertical distributions, of the quantities since the profiles themselves are maintained by the vertical transports or fluxes. The models used to relate profile measurements to fluxes, and additional parameters arising from these models, are briefly described below.

The models are empirical in nature and they are formulated using dimensional analysis once the determining parameters are defined. The general theory relating statistics of mean properties to vertical fluxes is the Monin-Obuhkov theory which predicts the following relationships between the mean gradients and the parameters u_*, T_*, and q_* defined by turbulent fluxes.

$$\frac{\partial \bar{u}}{\partial z} = \frac{u_*}{Kz} \phi_m \left(\frac{Z}{L}\right) \tag{1}$$

$$\frac{\partial \bar{T}}{\partial z} = \frac{T_*}{Kz} \phi_n \left(\frac{Z}{L}\right) \tag{2}$$

$$\frac{\partial \bar{q}}{\partial z} = \frac{q_*}{Kz} \phi_n \left(\frac{Z}{L}\right) \tag{3}$$

Here ϕ_m and ϕ_n are empirically determined functions and

$$u_* = (- \overline{uw})^{1/2}$$

$$T_* = -\overline{w\theta}/u_*\ , \ \theta \text{ is the temperature fluctuation}$$

$$q_* = -\overline{wq'}/u_*, \ q' \text{ is the specific humidity fluctuation}$$

$$L = \frac{\bar{T}_v\, u_*^{\,2}}{qk\ T_{*v}}\ , \qquad T_{*v} = T_* + .61q_*\ \bar{T}\ .$$

Recent observational results on the functions ϕ_m and ϕ_n have been summarized by Busch (1973). These functions are well defined for the over-land regime. The over-water functions, as they pertain to the stability influence, are also known, e.g., Paulson et al (1972) and Davidson (1974).

Profile measurements provide values of $\bar{u}$, $\bar{T}$, and $\bar{q}$ at various heights above the surface, normally spaced logarithmically. Therefore, the integrated forms of equations (1), (2), and (3) are those considered which are

$$u = \frac{u_*}{K}\left[\ell n\,\frac{Z}{Z_o} - \psi_m\left(\frac{Z}{L}\right)\right] \tag{4}$$

$$T = T_o + \frac{T_*}{K}\left[\ell n\,\frac{Z}{Z_o} - \psi_n\left(\frac{Z}{L}\right)\right] \tag{5}$$

$$q = q_o + \frac{q_*}{K}\left[\ell n\,\frac{Z}{Z_o} - \psi_n\left(\frac{Z}{L}\right)\right] \tag{6}$$

where

$$\psi_i\left(\frac{Z}{L}\right) = \int_{Z_o/L}^{Z/L} 1 - \psi_i(\xi)\ d_\xi\ , \quad i = m \text{ or } n$$

Often the ratio Z/L, which accounts for the stability influence, is replaced by the Richardson number

$$Ri = \frac{g}{T}\,\frac{\frac{\partial T}{\partial z}}{\left(\frac{\partial u}{\partial z}\right)^2} \tag{7}$$

which can then be determined from mean rather than fluctuating quantities. This is possible because the Richardson number is related to Z/L. These relationships, for different stability classifications, have also been summarized by Busch (1973).

Examinations of the integrated expressions indicate that the vertical distributions of wind, temperature and humidity should be logarithmic with the modification $-\psi(Z/L)$ due to stability, defined by Z/L or Ri. Over-land observational results for wind profiles for different stability conditions, defined by L, are shown in Figure 1.

For neutral or near neutral conditions $\psi_m(Z/L) \cong 0$ and the wind profile becomes

$$u = \frac{u_*}{k} \ln \frac{Z}{Z_o} \quad . \tag{8}$$

From this expression and previous expressions, the approach for examining profiles becomes evident. First, plots of wind speed, temperature and humidity versus $\ln(Z)$ should yield nearly straight lines with slopes of k/u_*. The slopes of these lines could then be used for estimating u_*. Secondly, the surface roughness parameter becomes important since, once u_* is known, Z_o determines the wind speed, $\bar{u}$, at a height Z. Surface roughness specification is an important consideration in profile analysis because, as can be seen in the expression below, Z_o is the determining parameter for the ratio of u_* to the wind speed at a height Z, since

$$\frac{u_*}{u} = \frac{k}{\ln \frac{Z}{Z_o}} \quad . \tag{9}$$

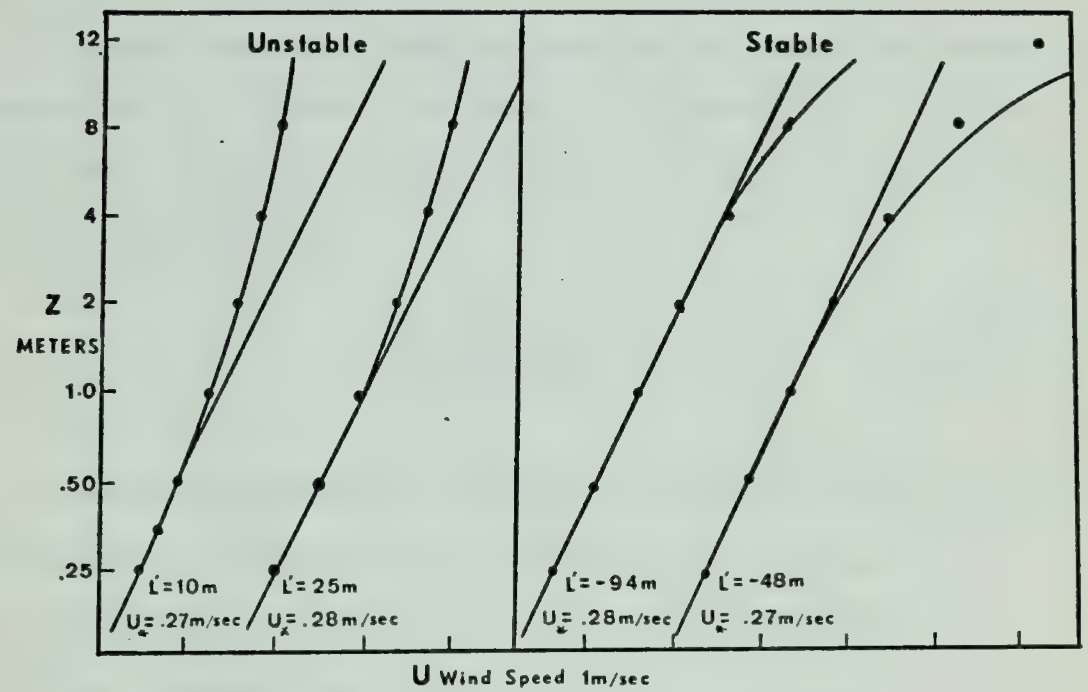

Unstable
Stable
12
8
4
Z 2
METERS
1.0
.50
.25
L′=10m
U*= .27m/sec
L′= 25m
U*= .28m/sec
L′= -94m
U*= .28m/sec
L′= -48m
U*= .27m/sec
U Wind Speed 1m/sec

Figure 1

The latter interpretation of Z_o is important in the specification of a drag coefficient at a given level. The drag coefficient is defined as

$$C_z = \left(\frac{u_*}{u_z}\right)^2 = \left(\frac{k}{\ln \frac{Z}{Z_o}}\right)^2 . \tag{10}$$

Hence, C_z and Z_o are related.

A final approach in examining profiles and parameters derived from them is to consider the stability influence, Z/L or Ri. The following expression shows that C_z is also a function of stability since, by definition,

$$C_z = \left[\frac{k}{\ln \frac{Z}{Z_o} - \psi(Ri)}\right]^2 \tag{11}$$

The above profile-related parameters, along with the profiles themselves, are examined for various predicted features. The analysis will include comparisons of results obtained by others with the shipboard results.

III. DESCRIPTION OF INSTRUMENTATION AND CALIBRATION PROCEDURES

A. DESCRIPTION AND MATCHING OF MEAN WIND SENSORS

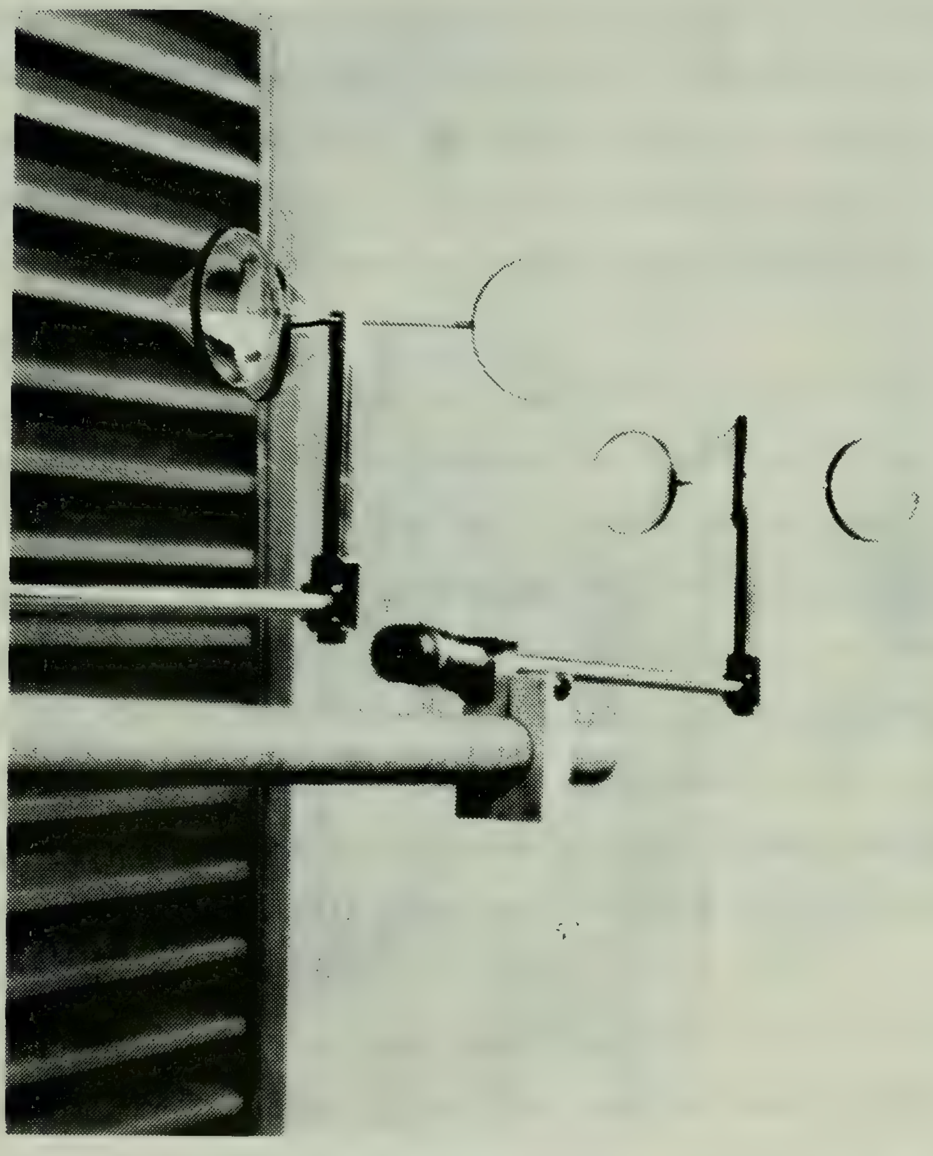
A Thornthwaite Associates cup anemometer wind profile register system model number 104 was used to measure the mean wind. The cups are plastic cones with aluminum reinforced frames (Figure 2). Each unit consisted of three such cups connected to an aluminum hub by stainless steel tubing. The anemometer shaft served as a shutter which interrupted a light beam and triggered a photoelectric cell.

Four matched anemometer sets were mounted aboard the R/V Acania for this experiment, each a lightweight cup assembly with low internal friction in order to prevent as much as possible inertial overshoot but have a low starting speed. The photocell transmitters were matched at the factory to an accuracy of $\pm$ 1 count per timing period.

Three anemometer cup assembly sets functioned normally throughout most of the experiment. A set screw holding the fourth assembly to the mast was evidently over-stressed and was subsequently lost in moderately heavy seas and strong winds while transitting from Monterey Bay to the experiment site.

B. DESCRIPTION AND CALIBRATION OF MEAN TEMPERATURE SENSORS

Mean temperatures at five levels were obtained using a Hewlett Packard Quartz thermometer, model HP-2801A, and HP-2850B probes. In each of the probes temperature sensitive quartz crystals are



C. W. Thornthwaite Anemometer Cups

Figure 2

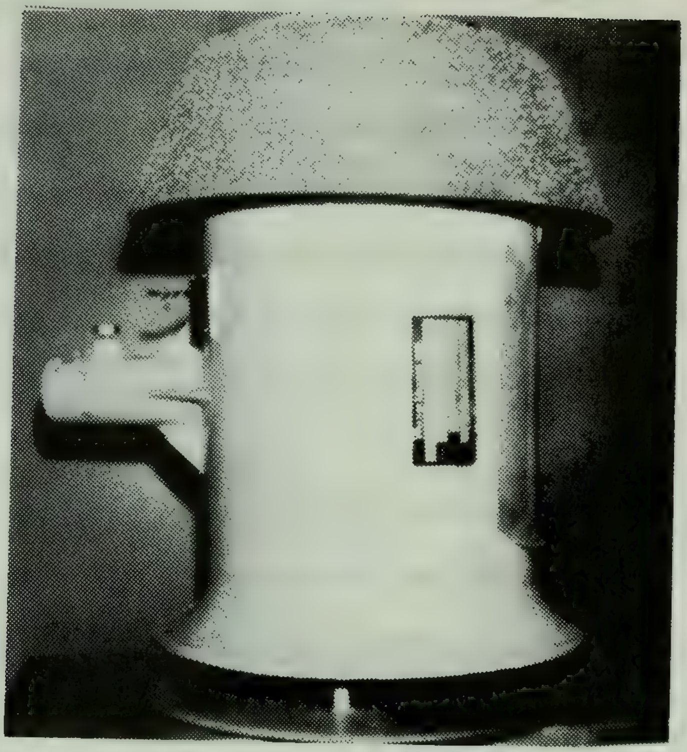
used as sensing elements. A temperature sensitive crystal oscillator generates a radio-frequency signal which is mixed with a similar radio-frequency signal generated by a very stable reference oscillator. The resulting beat frequency is then detected. The slope of the frequency versus temperature curve is established as near as possible to 1000 Hz per C. The sensor crystal is sealed in a 2-inch by 3/8-inch cylindrical stainless steel case, in a helium atmosphere. A 3.7 meter length of flexible coaxial cable is permanently attached to the probe (Figure 3).

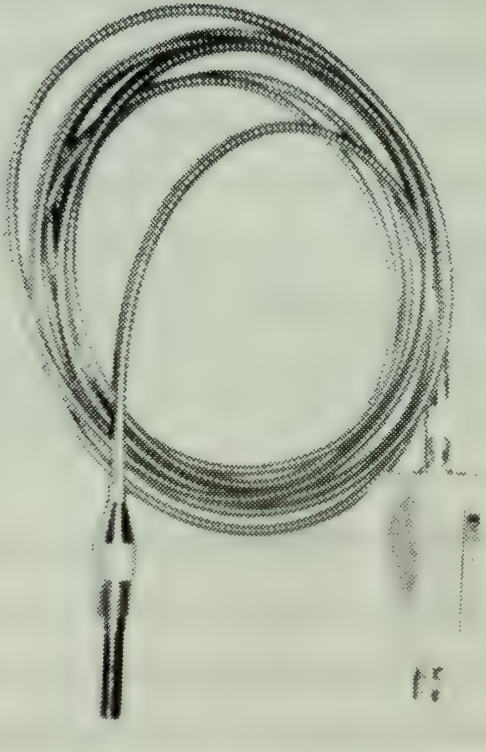
Climatological atlases were used to determine the range of temperatures, for calibration purposes, to be expected in the vicinity of San Nicolas Island during the latter part of September. It was determined that pre- and post-experiment calibrations of the five quartz sensors at 2C intervals from 14 to 22C would be sufficient. A platinum resistance wire thermometer in a temperature controlled circulating water bath was used as the standard to achieve calibration temperatures to accuracies of ± 0.001C. Such accuracy was necessary because small temperature gradients were expected over the sea.

In this experiment mean temperatures over ten-minute intervals were needed. Therefore calibrations were performed such that each calibration temperature was approached from both higher and lower values. It was observed that beyond three minutes there was no hysteresis effect.

The circulating water bath was the opposing temperature type. The water was alternately heated (electrically) and cooled (using liquid nitrogen) resulting in precise temperature control.

Weathermeasure
aspirated sensor
shelter





Quartz
Thermometer
Probe and
Oscillator

Figure 3

All sensors were suspended together in the controlled temperature bath with the platinum resistance wire probe in the center. The five quartz sensors were arranged symmetrically around the probe in a circle. Prior to the calibration loop, ranging from 14 to 22C, a distilled water ice bath was used to set the preset in the quartz thermometer and to adjust each of the sensor oscillators. The temperature calibration laboratory, liquid nitrogen and heater controls, Wheatstone bridge and platinum resistance wire probe are shown in Figure 4.

For calibration purposes the sensors were designated T_0, T_1, T_2, T_3, T_4. In order to provide a standard for the profile measurements that were planned, the bath temperature was adjusted at each calibration point so that T_0, the sea surface temperature in the experiment, indicated the exact temperature. In this manner T_0 was calibrated against the platinum resistance wire thermometer and each of the other sensors was then calibrated against T_0.

Tabular results of the post experiment calibration are shown in Table I along with correction factors that were applied to sensor readings. Calibration results indicated that over the 14 to 22C range the correction to achieve $\pm$ 0.005C accuracy was a constant for each sensor.

C. DESCRIPTION AND CALIBRATION OF HUMIDITY SENSORS

Relative humidity was measured using the Hygrodynamics Digital I hygrometer indicator and Dunmore-type lithium chloride sensors. The precision of these hygrosensors depends on the accurate measurement of the electrical resistance of the lithium chloride sensor

Temperature Calibration Laboratory

Figure 4

TABLE I

QUARTZ THERMOMETER CALIBRATION RESULTS

Preset for Quartz Thermometer 9469

2 October 1973

Calibration Point	T_0	T_1	T_2	T_3	T_4	$T_{Platinum}$
22C	22.000	22.080	22.047	22.126	22.005	22.030
20C	20.000	20.080	20.047	20.125	20.006	20.030
18C	18.000	18.079	18.047	18.127	18.006	18.025
16C	16.000	16.081	16.046	16.126	16.006	16.030
14C	14.000	14.075	14.050	14.126	14.007	14.030

Data Corrections Employed:

T_0	T_1	T_2	T_3	T_4
--	-.080	-.05	-.13	-.01

Color Coding to Sensor Location

T_0	Blue	Sea Surface
T_1	Gold	3.9
T_2	Red	7.7
T_3	Plain	12.7
T_4	Gray	14.0

which varies in proportion of the relative humidity to which it is exposed. A constant excitation voltage is supplied to the sensor by the indicator; the unit senses the change in resistance of the lithium chloride and converts that change into a voltage that is proportional to the relative humidity. A Dunmore type lithium chloride sensor is shown in Figure 5. The electronic circuitry used in these indicators provides automatic temperature compensation to render relative humidity readings to the following specifications:

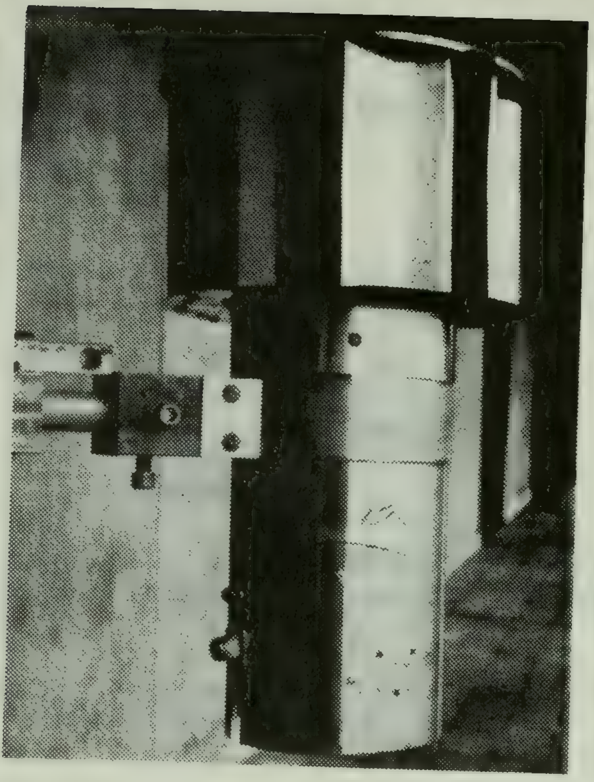
± 3% relative humidity below 90% relative humidity

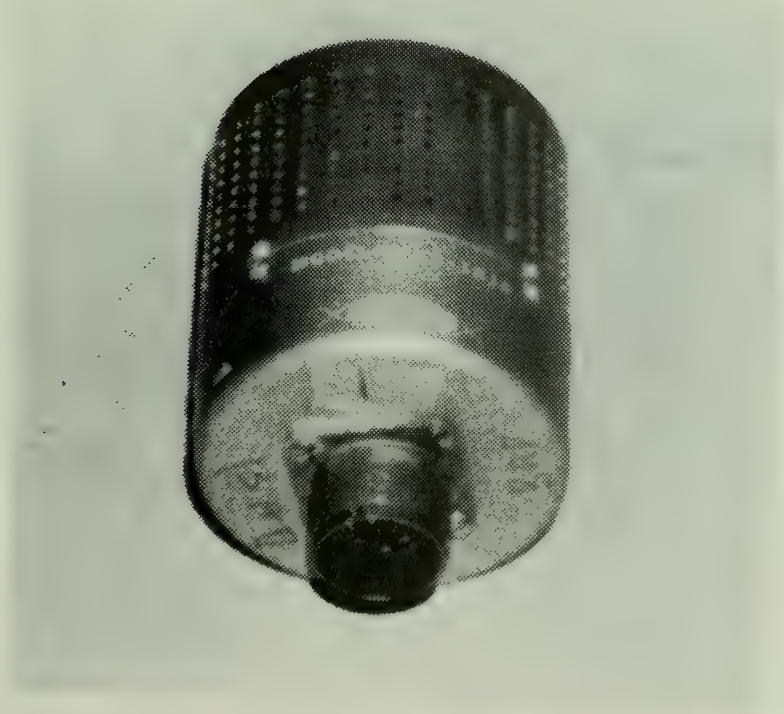
± 4% relative humidity above 90% relative humidity.

A Hygrodynamics Calibration Standard Chamber was used to calibrate the hygrosensors before and after the experiment. The chamber enabled one to have a known humidity against which the sensors were calibrated. The humidity in the chamber was controlled by using various saturated salt solutions. It is possible to determine the water vapor pressure maintained over such a solution for a given temperature when the solution is enclosed in a relatively confined space. The calibration procedures were those suggested in Hygrodynamics Technical Bulletin Number 5. Three different salt solutions were used in both calibrations. Potassium nitrite, ammonium sulphate, and potassium sulphate were chosen for calibration standard salt solutions since the range of relative humidities that they generate span the humidities that were anticipated during the experiment (50% to 97%). The calibration results are shown in tables II, III and IV.

The results indicate that sensors 2, 3, and 4 could detect relative humidity to accuracies of ± 3%. Comparisons of the pre- and

C. C. Breidert Company
Air-X-Hauster type 6L





Dunmore type
Lithium
Chloride
Sensor

Figure 5

TABLE II

MEAN RELATIVE HUMIDITY CALIBRATION RESULTS

$(NH_4)_2\ SO_4$ Salt Solution

Reference percent relative humidity and corresponding temperature for ammonium sulphate:

68F	77F	86F
80.6%	80.3%	80.0%

PRE-EXPERIMENT 16 SEPTEMBER 1973

Sensor	Temperature F	Relative Humidity %	Temperature T	Relative Humidity %	Corrected Mean % at 77F
1	66.3	70.3	75.2	79.0	79.0
2	70.8	79.2	75.9	80.7	79.3
3	73.5	78.7	75.7	79.5	79.1
4	74.0	77.5	76.0	78.0	77.7

POST-EXPERIMENT 5 OCTOBER 1973

Sensor	Temperature F	Relative Humidity %	Temperature T	Relative Humidity %	Corrected Mean % at 77F
1	70.9	99.1	77.8	97.0	98.0
2	75.6	81.0	80.6	81.4	81.2
3	77.2	80.7	78.7	80.3	80.5
4	--	--	78.8	80.3	80.3

TABLE III

MEAN RELATIVE HUMIDITY CALIBRATION RESULTS

KNO_2 Salt Solution

Reference percent relative humidity and corresponding temperature for potassium nitrite:

68F	77F	86F
49.0%	48.1%	47.2%

PRE-EXPERIMENT 16 SEPTEMBER 1973

Sensor	Temperature F	Relative Humidity %	Temperature F	Relative Humidity %	Corrected Mean % at 77F
1	74.3	47.3	75.8	47.5	47.2
2	73.9	47.8	75.5	48.1	47.8
3	73.8	47.3	75.8	47.5	47.2
4	72.8	45.9	74.3	47.2	46.2
	POST-EXPERIMENT		9 OCTOBER 1973		
1	71.2	57.4	79.0	57.0	57.6
2	74.3	47.5	78.7	48.0	48.0
3	77.6	47.7	80.3	47.1	47.3
4	78.4	49.3	80.2	48.8	48.9

TABLE IV

MEAN RELATIVE HUMIDITY CALIBRATION RESULTS

$K_2\ SO_4$ Salt Solution

Reference percent relative humidity and corresponding temperature for potassium sulphate:

68F	77F	86F
97.2%	96.9%	96.6T

PRE-EXPERIMENT 16 SEPTEMBER 1973

Sensor	Temperature F	Relative Humidity %	Temperature F	Relative Humidity %	Corrected Mean % at 77F
1	75.5	96.4	76.9	95.5	96.0
2	74.2	97.2	77.4	97.9	97.5
3	73.3	96.7	77.5	95.4	95.9
4	72.5	93.9	75.3	97.0	95.4

POST-EXPERIMENT 10-11 OCTOBER 1973

Sensor	Temperature F	Relative Humidity %	Temperature F	Relative Humidity %	Corrected Mean % at 77F
1	77.7	97.4	73.4	96.8	97.1
2	76.8	96.1	77.5	95.9	96.0
3	74.7	94.5	70.7	94.9	94.6
4	71.5	94.2	73.4	94.1	94.0

post-experiment calibration results for sensor number 1 clearly show that sometime prior to the second calibration the sensor failed.

IV. DESCRIPTION OF THE EXPERIMENT

A. BACKGROUND

The shipboard observations were made from the Naval Postgraduate School's research vessel, R/V Acania, operated by the Department of Oceanography. The R/V Acania is 48.4 meters long, has a beam of 6.5 meters and a draft of 2.7 meters.

The meteorological observation experiment was part of an optical propagation investigation involving personnel and equipment from the Physics, Meteorology, Oceanography and Mechanical Engineering departments at the Naval Postgraduate School. In the combined experiment, the majority of the meteorological instrumentation was mounted on a mast located forward on the R/V Acania, Figure 6. Optical propagation equipment, including a gyro stabilized helium neon laser, was also mounted aboard the R/V Acania and detection equipment was installed on the San Nicolas Island shoreline.

B. LOCATION OF SENSORS

Sensor arrangements were designed to obtain sea surface temperature, mean wind, mean temperature and mean humidity at four levels in the air.

The sea surface temperature probe was trailed in the water from the end of a 5.8 meter boom, 18.8 meters aft, amidships on the starboard side. At that distance from the side of the ship the sensor was assumed not to be affected by any overboard discharges or the Acania's wake. Attached to the last 3.4 meters of the sea surface

Research Vessel Acania

Figure 6

temperature probe's cabling, secured with clamps and tape, was a length of flexible plastic tubing (outside diameter 2.5 centimeters, inside diameter 2.2 centimeters). Its flexibility enabled it to keep the sensor at the right depth quite well. The probe generally remained at approximately five centimeters below the surface and varied from that depth by only about ± two centimeters, judged on the basis of the immersion of the flexible tubing.

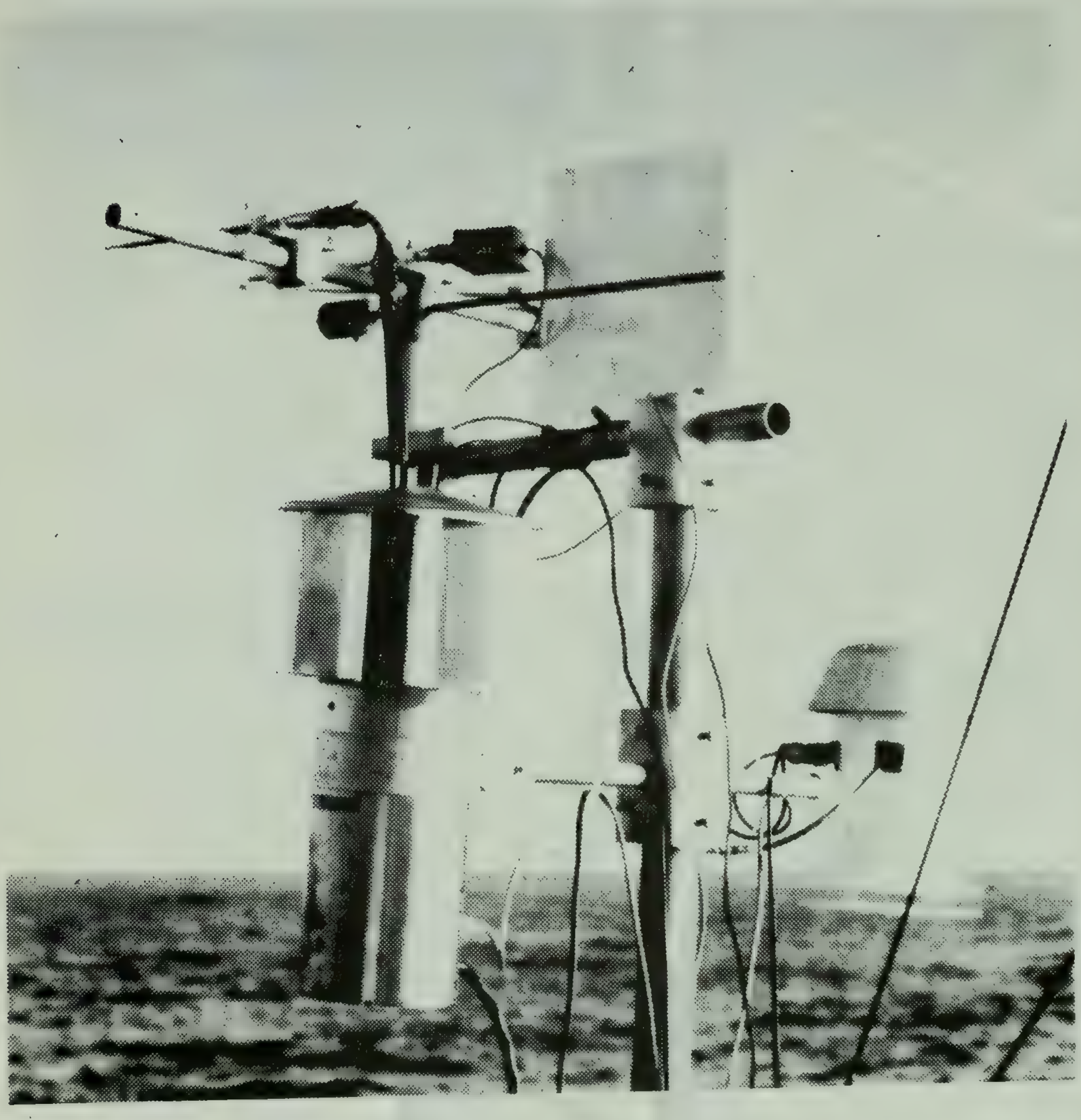
At each of the four measurement levels in the air were: a cup anemometer on a vane assembly, a quartz thermometer probe, and a hygrosensor. The latter two were in separate aspirated radiation shelters, described later, which were fixed to the tower on either side of the vane assembly. On the forward end of each vane rod a cup anemometer assembly was mounted so that it rotated with the vane (Figures 7 and 8).

The first sensor assembly (level 1) was mounted at the top of a 1.2 meter steel pole at the stem of the ship and the remaining air sensors were mounted on the tower which was 4.4 meters aft of the stem. Figure 9 shows the mounting arrangement and heights of the various sensors.

C. ASPIRATORS

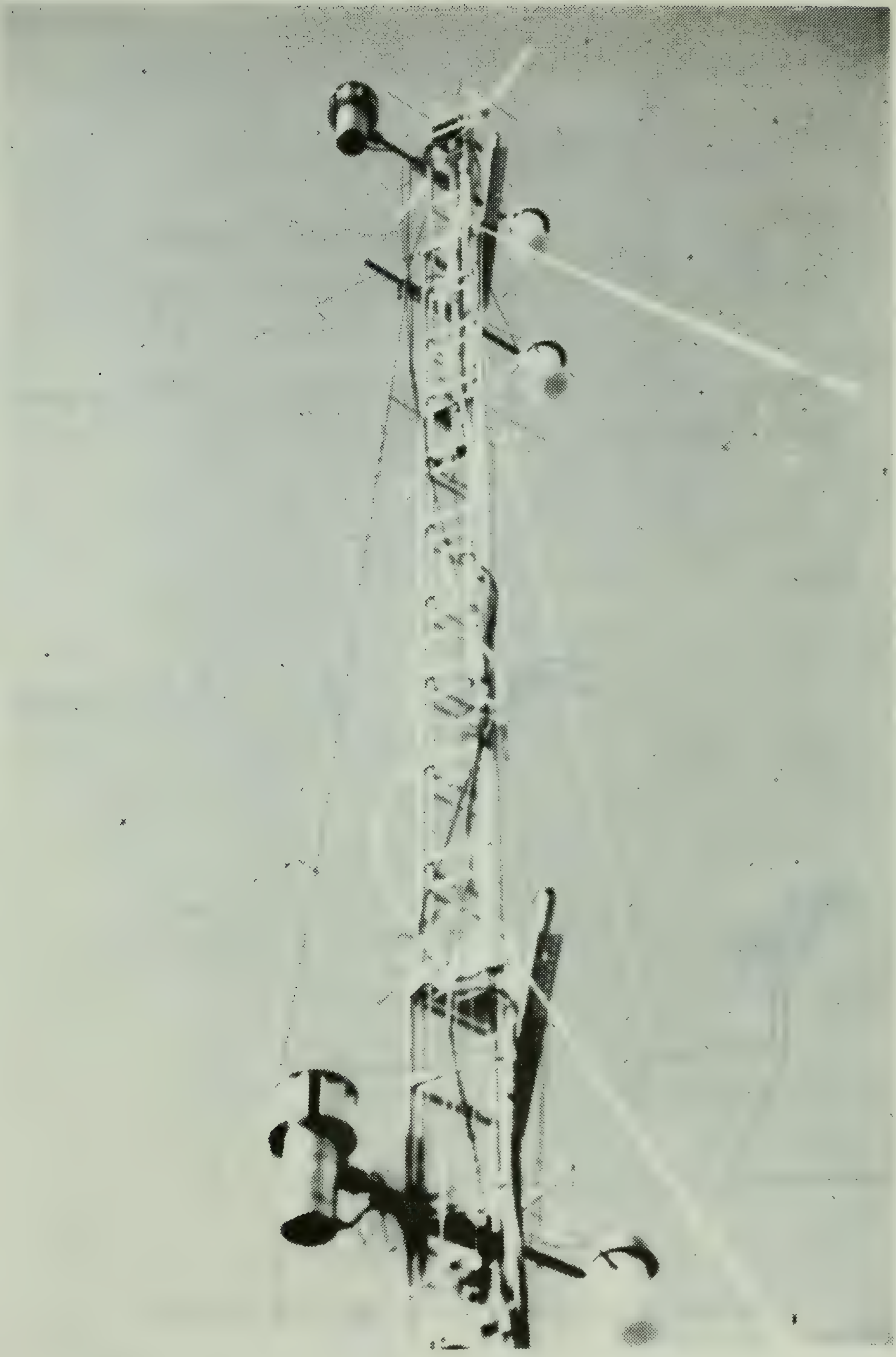
Uniform aspiration of the quartz thermometer and hygrometer probes was important to ensure that measured temperatures and humidities were typical of the air at that level. Improper or non-uniform aspiration is known to produce spurious results.

In this experiment two different types of aspirated housings were used. The quartz probes in the air were mounted in Weather-measure Corporation IS6 motor aspirated radiation shields



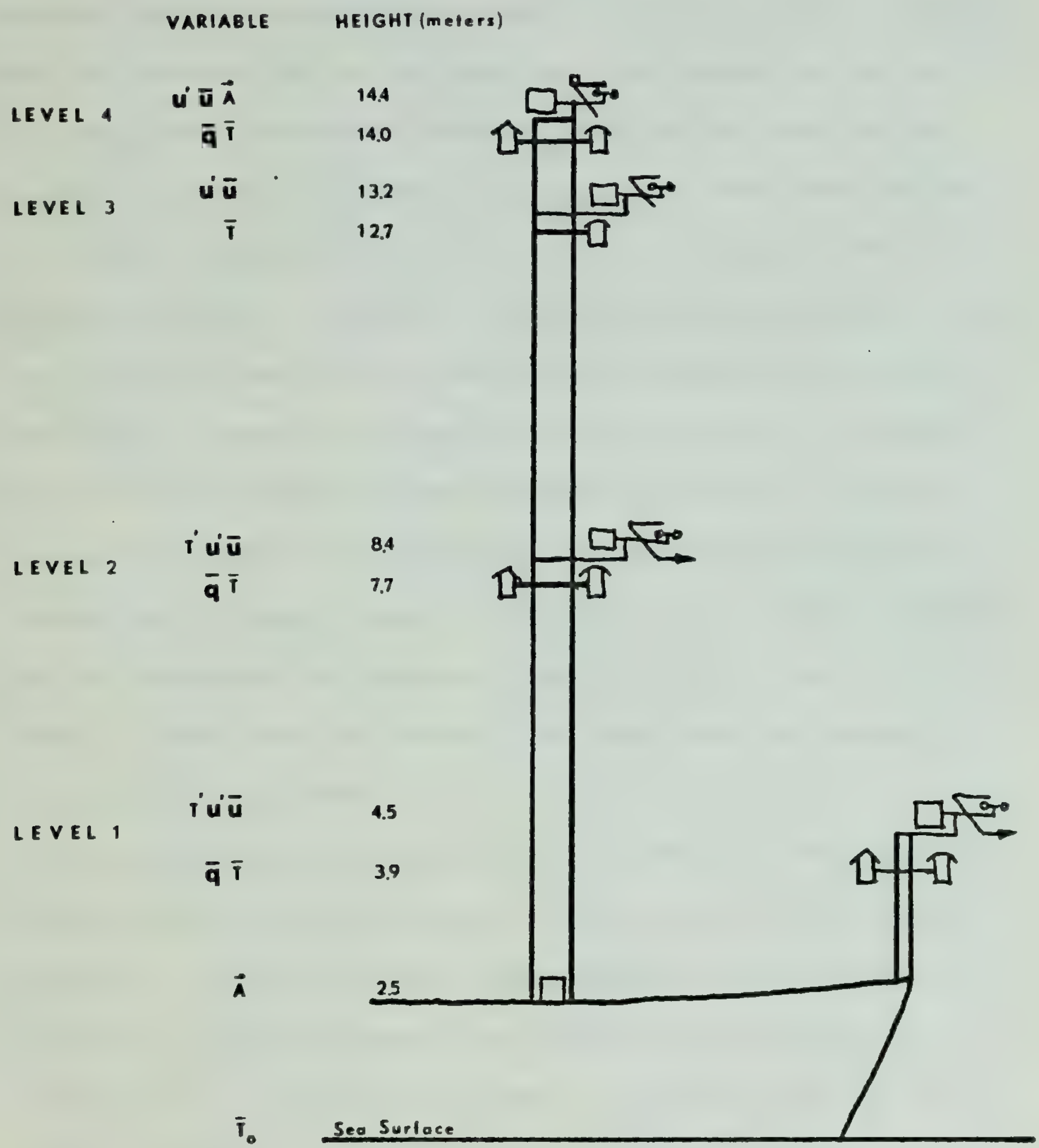
Level 1 Meteorological Instrument Array

Figure 7



Meteorological Instruments Mast showing Levels 2, 3, and 4.

Figure 8



Mounting Arrangements for Meteorological Sensors

Figure 9

(Figure 5). The shields were constructed of aluminum and painted with white epoxy enamel. They are designed to eliminate the effect of solar radiation on the probes. Air is drawn in through the bottom, passing through a small opening where the probe is located, and then through the fan and expelled via an opening at the top. Post experiment dismantling revealed that the fan motor for one housing (level three in Figure 9) was mounted upside down so that the airflow through the radiation shield was reversed. This flow pattern resulted in inaccurate (higher) temperature readings since the air passed over the fan motor and was warmed before reaching the sensor. Inspection of one fan motor (for sensor T_2) revealed that one of the four fan blades was severely chipped. The unbalanced fan did not rotate and the lack of ventilation resulted in incorrectly higher temperature readings due to radiation heating. The fans and motors for sensors T_1 and T_4 (levels 1 and 4 in Figure 9) were installed correctly and functioned satisfactorily throughout the experiment.

The hygrosensors were housed in C. C. Breidert Company Air-X-Hausters type 6L, shown in Figure 5. The housing is designed to function as a radiation shield and to protect the sensors from the effects of salt water spray. The shields are constructed of aluminum and are aspirated by a small A. C. motor. The air is drawn in through a coarsely filtered opening at the base, then around the hygrosensor through the fan motor and out the top. All three hygrosensors and their corresponding motor aspirated shields apparently functioned normally throughout the data collecting period. The hygrosensor nearest the sea surface got wet frequently

during a four- to six-hour period of the return transit due to heavy seas. This was thought to account for its inoperative condition after the experiment.

D. ELECTRONIC LABORATORY AND CABLES

Sensor electronics and recorders were set up in a laboratory space located all the way aft on the main deck of the R/V Acania. The mean sensor displays are shown in Figure 10.

The sea surface temperature probe required 45.7 meters of cabling and the other sensors each required 61 meters of cabling. All sensor cabling was shielded to ensure signal fidelity.

E. OTHER MEASUREMENTS

Other meteorological measurements made in conjunction with the profile observations were simultaneous measurements of u' and T' at various levels. These measurements, while not made on a continuous basis, were made during each of the data runs and are described by Johnston (1974). Also, six accelerometers were used to measure the ship's motion in order to determine its effect on the meteorological data collected. These measurements are described by Welsh (1974).

F. THE EXPERIMENT

1. Synopsis

The experiment lasted ten days. The first six days (13-18 September 1973) were used to load and install the electronics and recording equipment, install the cables, and mount and test the sensors. Transits to and from the San Nicolas Island experiment site each took one day and two full days (20-21 September 1973) were

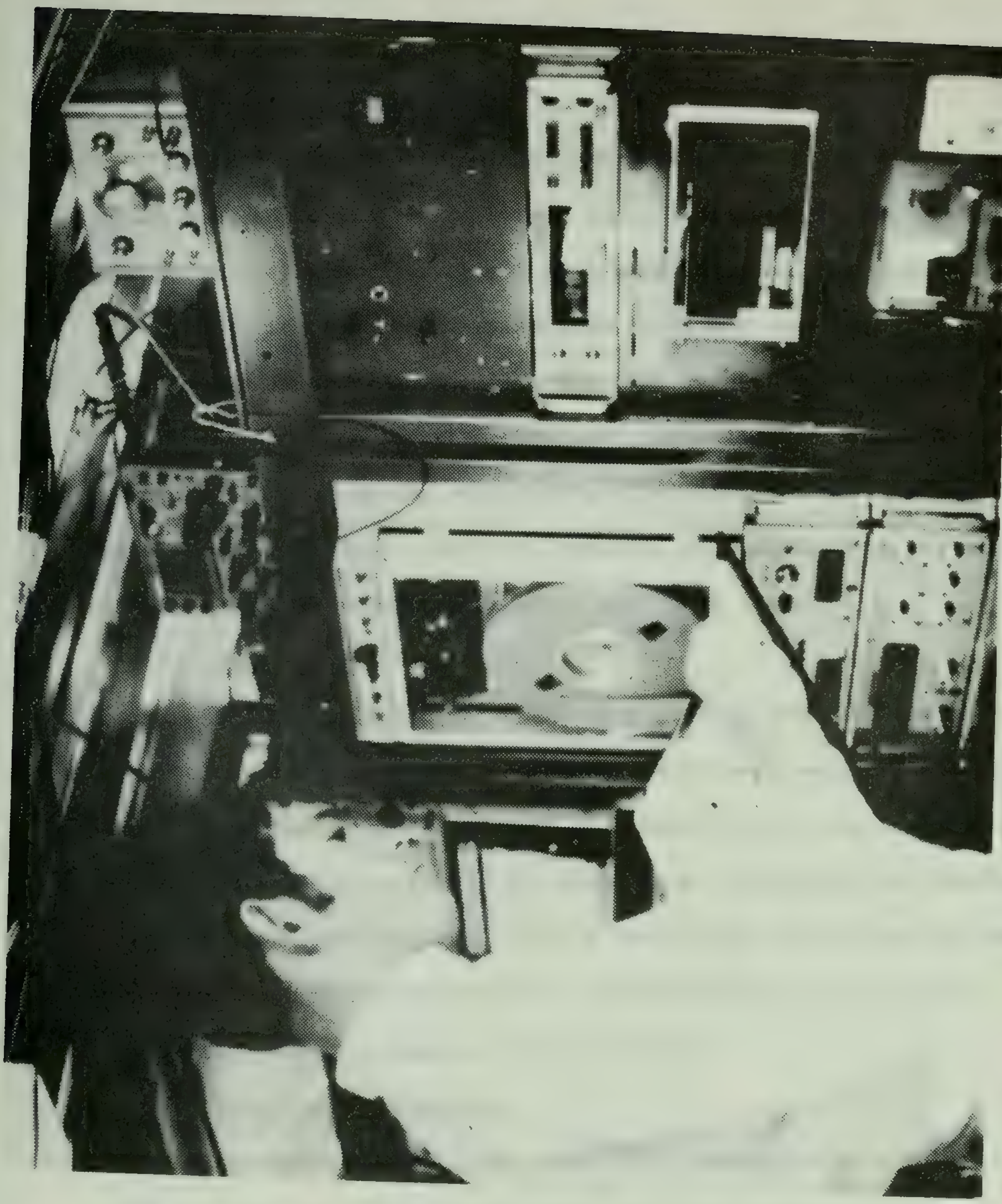


Figure 10

devoted to data collection in the vicinity of San Nicolas Island.

2. Transit and Anchorage

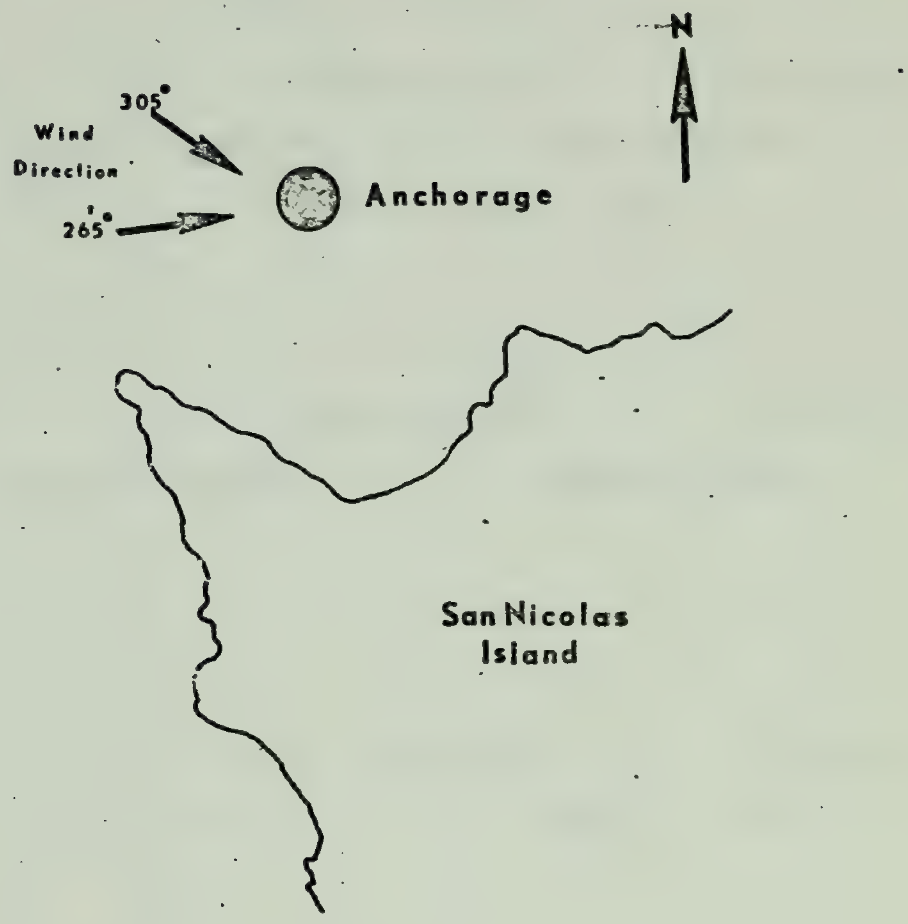
Throughout the transit from Monterey Bay to San Nicolas Island, which took approximately 24 hours, checks were made on the equipment. During most of the observations that were analyzed, the Acania was anchored in ten fathoms of water 1600 yards off the northwest tip of San Nicolas Island (Figure 11). The true wind at the beginning of the experiment was from the west northwest (265° to 305° TRUE), and remained so throughout the experiment. The fetch was unlimited. The data runs are listed in Table V, and will be described in the sections that follow. All times referred to are local time.

3. Data Run 1

During the first data run, from 0945 to 1150 20 September, mean relative humidity and wind measurements were made at three levels, and mean temperature measurements were made at the four levels in the air and at the sea surface. All data taken throughout the experiment were for ten-minute periods. During this first run it was noticed that the temperature sensors at 7.7 meters and 12.7 meters were apparently giving erroneously high readings.

4. Underway Observations

At 1200 the Acania proceeded on a westerly course (into the wind and sea) for about three hours, and then returned (with the wind and sea astern for three hours) to the anchorage location off San Nicolas Island. During this time an effort was made to make observations. While proceeding into the wind the mechanical counters for the anemometer cups could not keep up whenever the relative wind exceeded 30 knots. Also while on this course waves breaking over the



Western end of San Nicolas Island showing anchorage location and range of wind directions observed during the experiment.

Figure 11

TABLE V

SUMMARY OF DATA RUNS

Data Run 1 — 20 September 1973 — 0945-1150

Variables Measured	Number of Levels
$\bar{T}$	5
$\bar{q}$	3
$\bar{u}$	3
u'	4

Data Run 2 — 20 September 1973 — 2015-2140

Variables Measured	Number of Levels
$\bar{T}$	5
$\bar{q}$	3
$\bar{u}$	2
u'	3

Data Run 3 — 20-21 September 1973 — 2315-0045

Variables Measured	Number of Levels
$\bar{T}$	5
$\bar{q}$	3
$\bar{u}$	3
u'	3
T'	1

Data Run 4 — 21 September 1973 — 0630-0750

Variables Measured	Number of Levels
$\bar{T}$	5
$\bar{q}$	3
$\bar{u}$	3
u'	2

bow created considerable amounts of spray resulting in excessively high relative humidities being observed at the lower two levels. The sea surface temperature sensor remained approximately five centimeters underwater the vast majority of the time; only the largest waves occasionally caused it to break the surface momentarily. The other temperature sensors seemed to function normally with the ship moving into the wind and seas, but the effects of the high relative wind and spray on the mechanical cup counter and hygrosensors, respectively, obviated any data taking under those conditions. While travelling with the wind and seas the ship's own stack gases were blown across the temperature and humidity sensors resulting in erroneous readings. The adverse effect on the anemometer data on this course was the blocking and channelling of the wind caused by the ship's superstructure.

5. Data Runs 2, 3, and 4

The Acania returned to the anchorage at sunset, 20 September, and the second data run commenced at 2015. Mean wind was obtained at two levels, relative humidity at three levels, and temperature at five levels. Mean temperature data at 7.7 and 12.7 meters were again anomalously high relative to the other levels. The erroneously high temperatures at these two levels persisted throughout the experiment and were not understood until post experiment dismantling and inspection of equipment revealed the sources of the problems (detailed under Part IV C Aspirators).

Data run three was begun at 2320 and lasted an hour and a half. The equipment functioned as it had for the second run except

that for the last 50 minutes mean wind speed measurements were again available at three levels. Data run four, the final data run, began at 0655, 21 September. All mean sensors and equipment were functional as was the case for the last part of run three.

6. The Return Transit

Data run four was completed at about 1040, 21 September. At that time the ship made a brief (less than two hours) run around the northwest tip of the island, and, following that, began the 27 hour return transit to Monterey. During the underway time the various conditions described in paragraph three persisted. Excessive relative wind speeds, spray, stack gases, and the shielding effect of the ship's superstructure resulted in erroneous data.

Observations made during the four successful data runs of this experiment provided six hours and 20 minutes of simultaneous measurements of mean temperature, mean relative humidity, and mean wind speed. The data are tabulated in Appendix A.

V. ANALYSIS

A. PROFILES OF VIRTUAL POTENTIAL TEMPERATURE, $\bar{\theta}_v$, AND MEAN WIND, $\bar{u}$

Virtual potential temperature was computed as follows from observations of the temperture, $\bar{T}(Z)$, the relative humidity, $\overline{RH}(Z)$, and the pressure, $\bar{P}$. Integration of the Clausius-Clapeyron equation (Hess, 1959) yields

$$\ell n \left[\frac{e_s}{6.11}\right] = \frac{m_v L}{R^*} \left(\frac{1}{273} - \frac{1}{T}\right) \tag{12}$$

where $e_s \equiv$ saturation vapor pressure

$m_v \equiv$ molecular weight of water vapor

$L \equiv$ latent heat of evaporation

$R^* \equiv$ universal gas constant

but

$$RH = \frac{e}{e_s} \times 100 \tag{13}$$

where $RH \equiv$ relative humidity

$e \equiv$ vapor pressure

A combination of (12) and (13) yields

$$e = \frac{RH}{100} \times 6.11 \exp \left[\frac{m_v L}{R^*} \left(\frac{1}{273} - \frac{1}{T}\right)\right] \tag{14}$$

An approximation of the specific humidity, q, was then computed using the expressions from Hess (1959):

$$q = 0.622 \left(\frac{e}{P}\right) \tag{15}$$

where e was calculated from $\bar{T}$ and $\overline{RH}$ in Equation (14). The mean pressure was taken from synoptic analyses produced by Fleet Numerical Weather Central. The analyses used were those for the current six-hour period.

The virtual temperature is:

$$T_v = \left[\frac{1 + \frac{e}{p}}{1 + 0.622 \frac{e}{p}} \right] T \qquad (16)$$

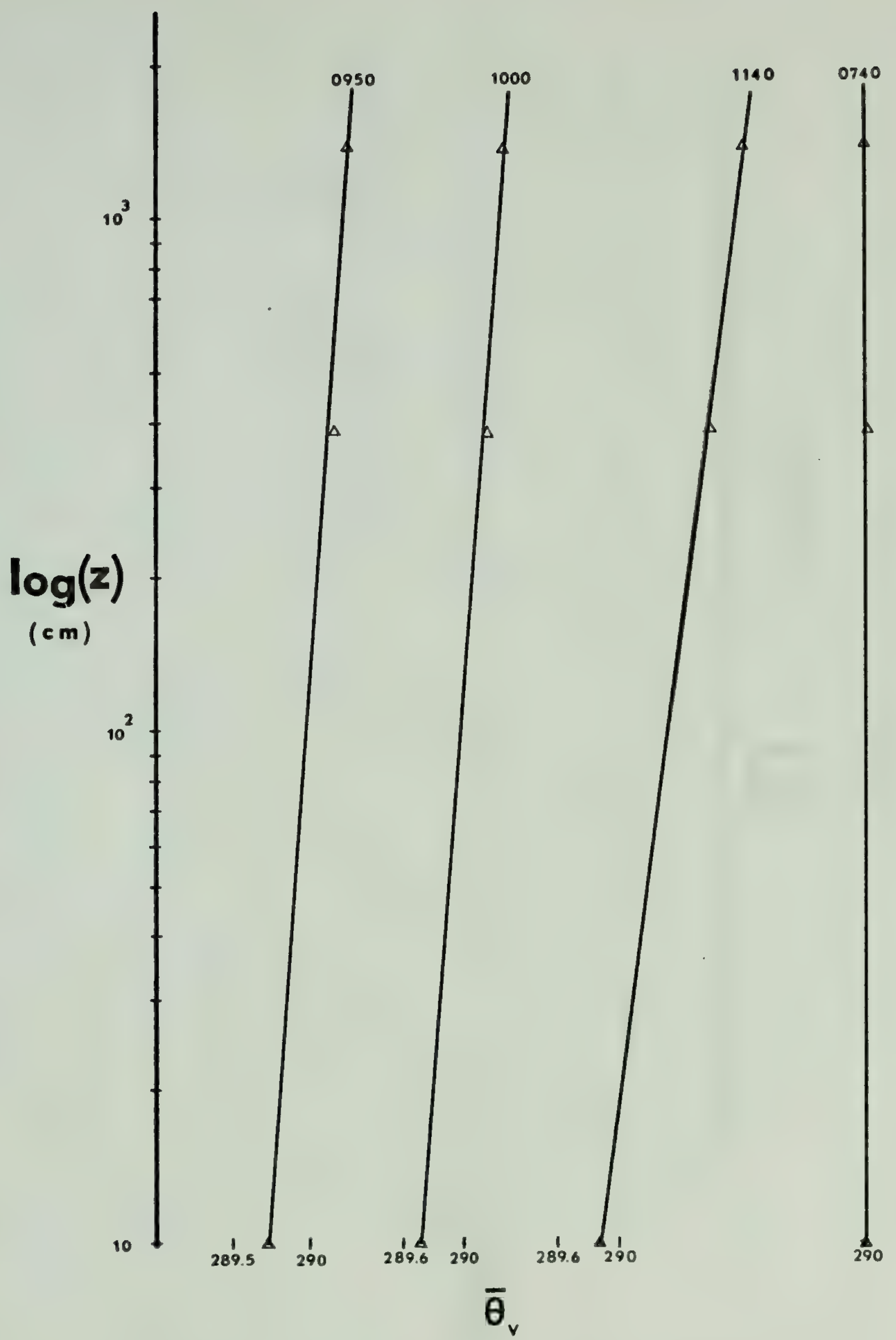
and the virtual potential temperature is

$$\bar{\theta}_v (Z) = \bar{T}_v (Z) + 0.0098Z \qquad (17)$$

where Z = the height in meters and 0.0098 = the adiabatic lapse rate in °K/meter. The computer program used to compute $\bar{\theta}_v$ (Z) appears in Appendix B.

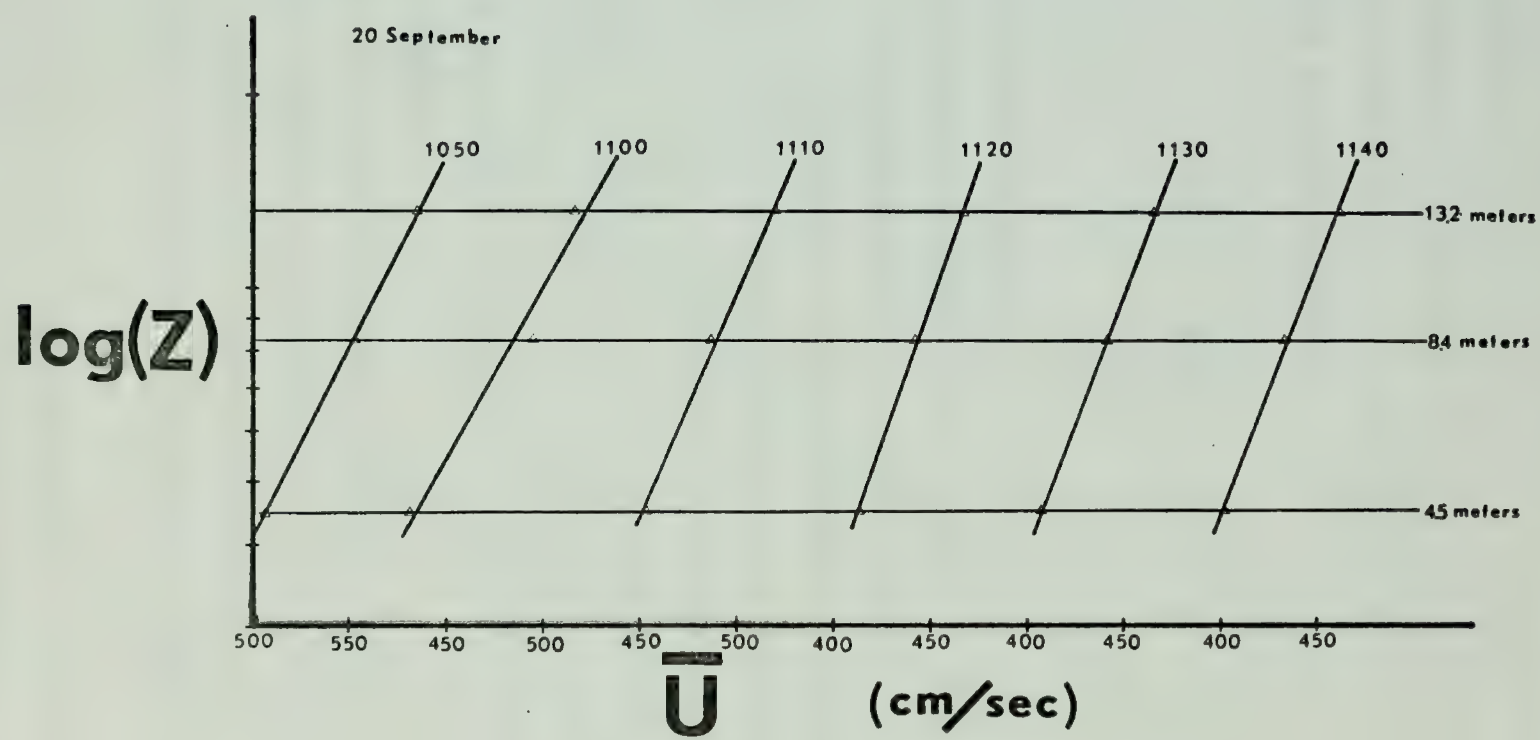
The logarithmic profile, introduced in Section II, is expected for vertical distributions of temperature and humidity as well as mean wind. Badgley et al (1968) observed logarithmic profiles over the Arabian Sea in examinations of 110 profiles of wind speed, temperature, and specific humidity. Sheppard et al (1972) also reported logarithmic profiles for the mean wind, potential temperature and specific humidity for observations off Lough Neagh, Northern Ireland.

Sample profiles of $\bar{\theta}_v$ obtained from shipboard measurements in this experiment appear in Figure 12. Sample profiles of the mean wind appear in Figure 13. They appear to agree with the logarithmic profile predictions.



Sample Profiles of Virtual Potential Temperature

Figure 12



Sample Mean Wind Profiles

Figure 13

Parameters of interest which can be derived directly from the mean wind profiles are Z_o, the roughness length, and u_*, the friction velocity. Examples of the graphical extrapolation technique used to compute Z_o are shown in Figure 14. The friction velocity, u_*, is calculated from $\bar{u}$ values as follows:

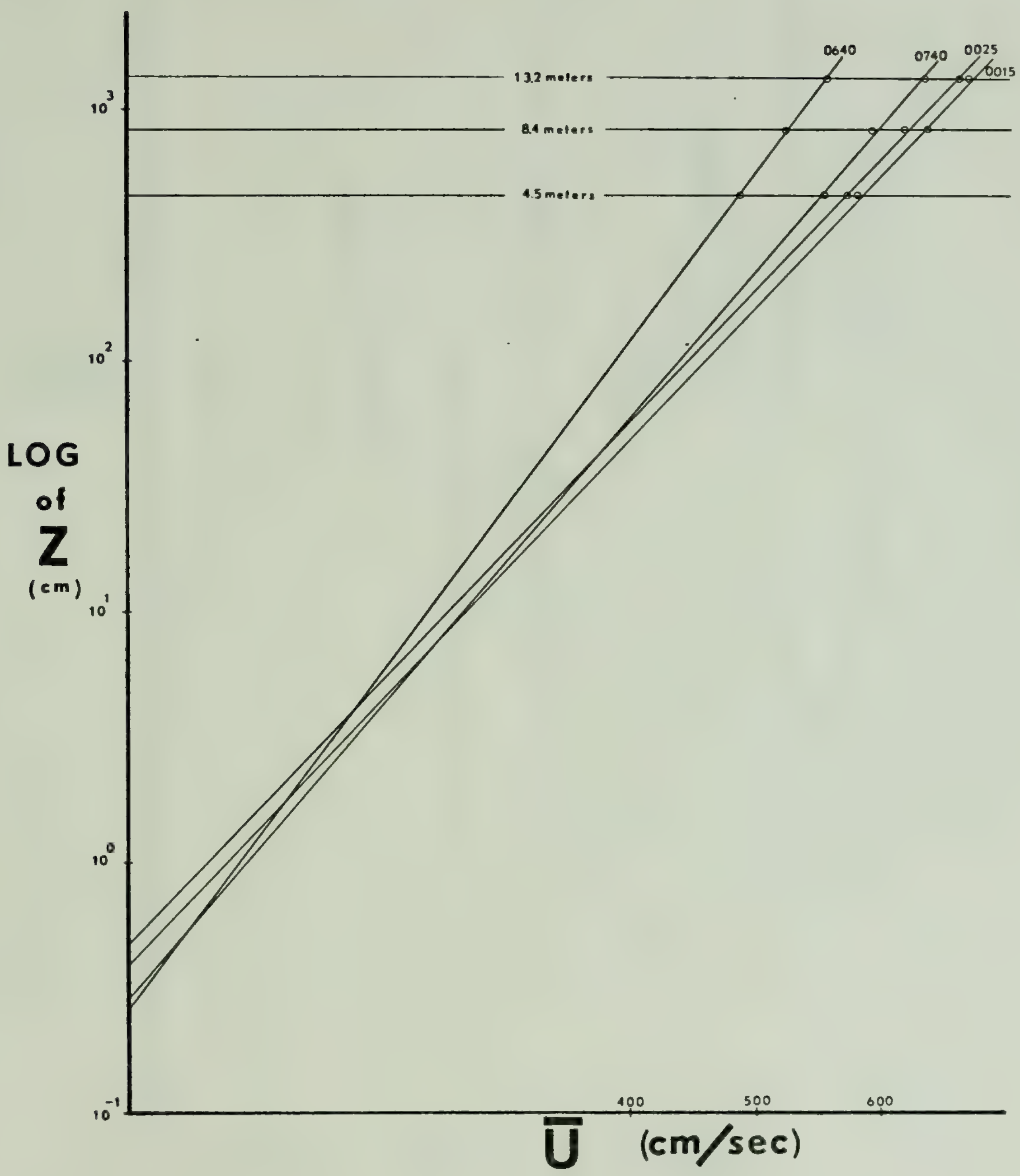
$$\frac{u_*}{k} = \frac{u_2 - u_1}{\ell n \left(\frac{Z_2}{Z_1}\right)} \tag{18}$$

assuming near-neutral conditions.

The appropriateness of Equation (18), the near-neutral stability expression, was established based on the narrow range of Richardson numbers that were observed during the experiment. Richardson numbers for the shipboard results were all close to zero, the neutral value. In order to use a geometric mean height of 7.5 meters and compare with De Leonibus' (1971) results, the heights chosen were $Z_2 = 14.0$ and $Z_1 = 3.9$ meters. The winds were extrapolated to these levels on the basis of the logarithmic profile. A value of 0.4 was used for the von Karman constant.

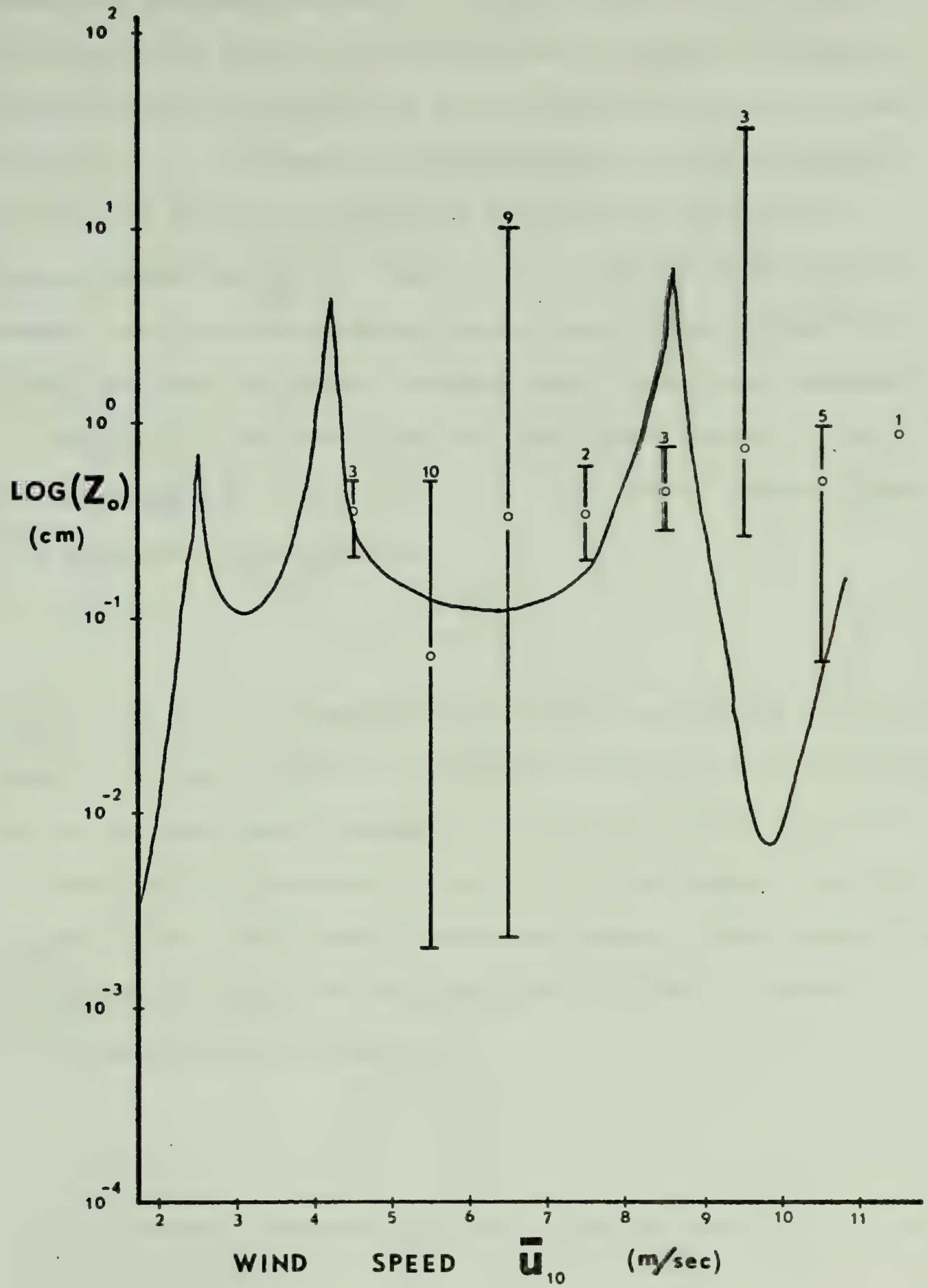
Ruggles (1970) examined numerous over-water Z_o values obtained from a stable buoy during a developing sea. His results on log Z_o versus $\bar{u}_{10}$ appear in Figure 15 along with shipboard results from this experiment, given in terms of the mean and range for grouped data.

Ruggles gave possible physical explanations for the peaks which occurred in his results. The first peak was suggested to correspond to the minimum wind required to generate waves, the second to the



Sample Z_o Extrapolations

Figure 14



10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
LOG(Z_o)
(cm)
3
10
9
2
3
3
5
1
2 3 4 5 6 7 8 9 10 11
WIND SPEED $\bar{u}_{10}$ (m/sec)

Figure 15

transition from capillary waves to gravity waves, and the third to the formation of white caps. He cautioned too strong an acceptance, however, since "the evidence is far too meager and the argument far too tenuous, ..., to make this assertion with any firm conviction." The means of 36 shipboard values of Z_o fall in the vicinity of Ruggles' values for Z_o, but peaks are not evident. It is significant, however, that there is agreement between these values obtained from a ship, and those of Ruggles, obtained from a more stable platform.

Many studies have dealt with the relationship between Z_o and u_*. The motivation for these studies was a suggestion by Charnock, based on a dimensional argument, that

$$Z_o = \frac{a\, u_*^2}{g} \quad . \tag{19}$$

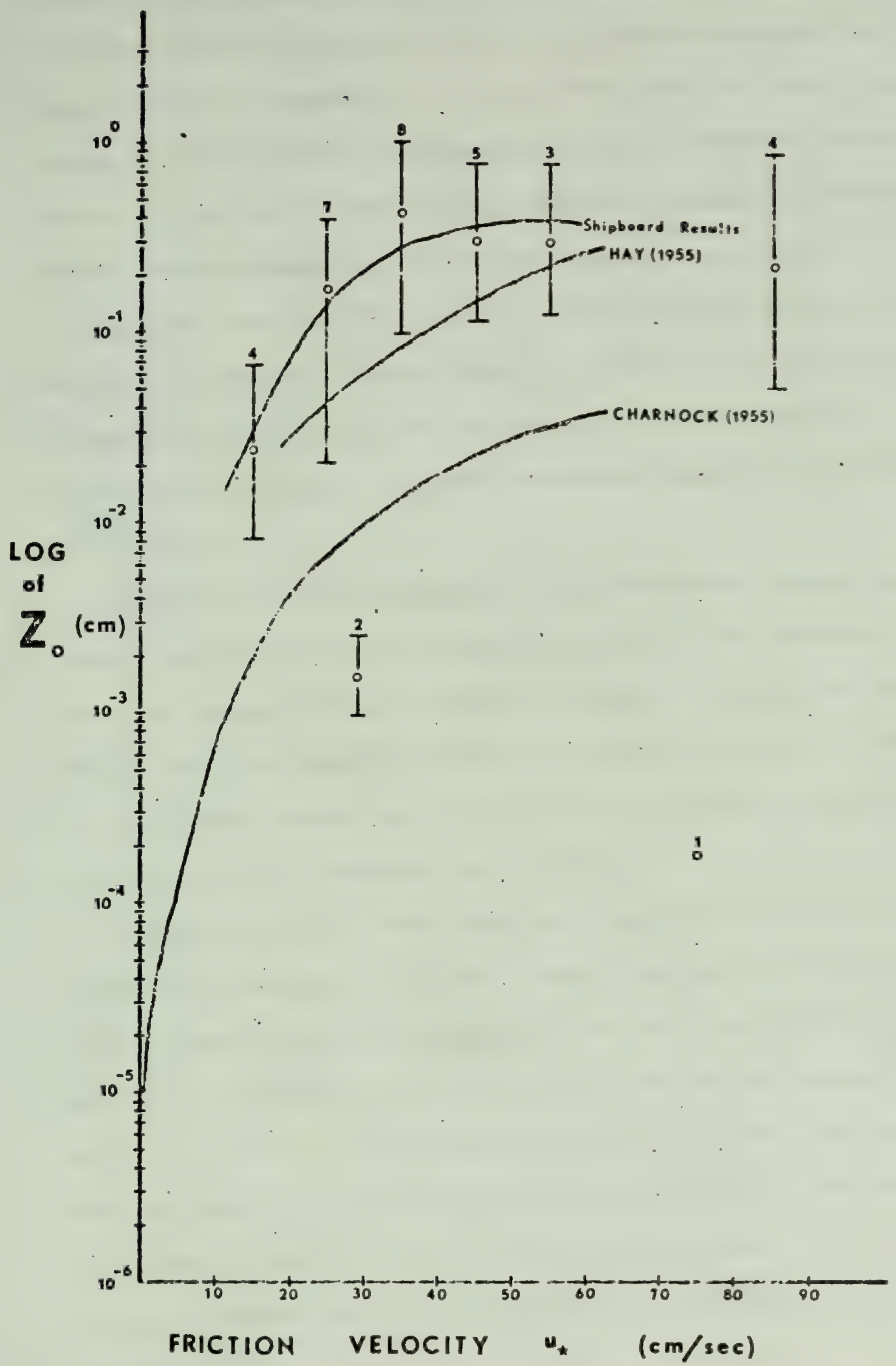
Relations of this type observed by Hay (1955) and Charnock (1955) are compared in Figure 16 with the shipboard results. The curve delineating the shipboard results generally parallels the other two curves. In comparison with Charnock's values for Z_o, the shipboard results are, in some places, a full order of magnitude larger. There appears to be more agreement between the shipboard results and Hay's results.

The drag coefficient defined as

$$C_z = \frac{u_*^2}{u_z^2} \tag{20}$$

is often examined instead of Z_o since for neutral conditions, C_z is related to Z_o by

$$C_z = \left[\frac{k}{\ln \frac{Z}{Z_o}} \right]^2 \quad . \tag{21}$$



LOG
of
Z o (cm)
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
Shipboard Results
HAY (1955)
CHARNOCK (1955)
8
7
5
3
4
4
2
1
10
20
30
40
50
60
70
80
90
FRICTION VELOCITY u* (cm/sec)

Figure 16

Comparisons were made between shipboard and other C_z results at two different heights, 10 and 7.5 meters. C_{10} results reported by Ruggles (1970), Sheppard et al (1972), Badgley et al (1968), and Denman and Miyake (1973) are compared with the shipboard results in Figure 17. As was the case for Z_o, there is considerable agreement between the shipboard C_{10} results and Ruggles' C_{10} results.

Sheppard et al's (1972) results, which do not show the scatter of Ruggles, extend over a large range of $\bar{u}_{10}$ values (2.0 to 15.0 mps). The mean of the shipboard results are higher than Sheppard et al's but increasing C_{10} with increasing wind speed is evident in both sets.

Badgley et al (1968) presented drag coefficient results for near neutral conditions over the Arabian Sea. They also observed C_z to generally increase with increasing wind speed. Comparisons of their results with the shipboard results also indicate that the latter are too high. There appears to be more agreement, however, than there is with the results of Sheppard et al (1972).

Denman and Miyake (1973) reported drag coefficient results for shipboard measurements obtained at Ocean Station PAPA from the Canadian Weathership CCGS Vancouver. The drag coefficient (C_{10}) was determined, by the dissipation technique, to have an average value of $(1.63 \pm 0.28) \times 10^{-3}$ for wind speeds up to 17 mps. Shipboard results, Figure 17, from Denman and Miyake show C_{10} to be constant, and generally smaller than C_{10} values of the present study. There is more agreement with these than there is with Badgley et al's results.

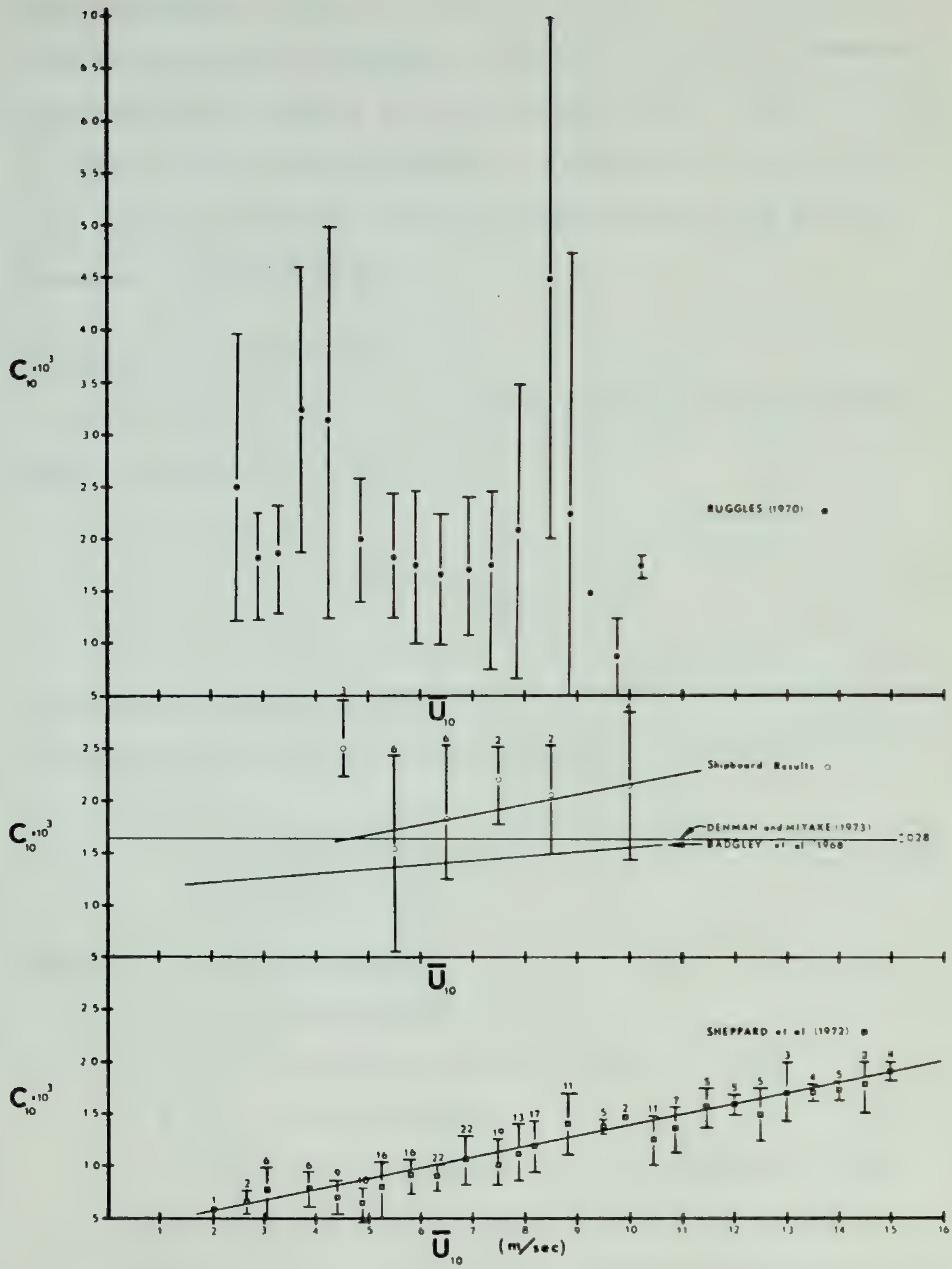

RUGGLES (1970)
Shipboard Results
DENMAN and MIYAKE (1973)
BADGLEY et al 1968
±.028
SHEPPARD et al (1972)
$C_{10} \times 10^3$
$\overline{U}_{10}$ (m/sec)

Figure 17

De Leonibus (1971) reported a considerable number of drag coefficient results for 7.5 meters above the sea surface observed from Argus Island Tower (45 kilometers southwest of Bermuda). Graphical comparisons of his results and the shipboard results appear in Figure 18. The shipboard drag coefficients are generally higher, but both plots exhibit considerable scatter. There appears to be greatest agreement at low wind speeds.

B. STABILITY CONSIDERATIONS

The Richardson number is frequently used as a measure of atmospheric stability and is defined as

$$Ri = \frac{g}{\bar{T}} \frac{\left(\frac{\partial \theta}{\partial Z}\right)}{\left(\frac{\partial \bar{u}}{\partial Z}\right)^2} \quad . \tag{22}$$

The Richardson number was computed for a height of 7.5 meters using the profile data obtained during the experiment by the expression:

$$Ri = \frac{g(\theta_2 - \theta_1)}{\bar{T}(\bar{u}_2 - \bar{u}_1)^2} \sqrt{Z_1 Z_2} \quad \ell n \frac{Z_2}{Z_1} \tag{23}$$

where Z_1 = 3.9 meters

Z_2 = 14.0 meters

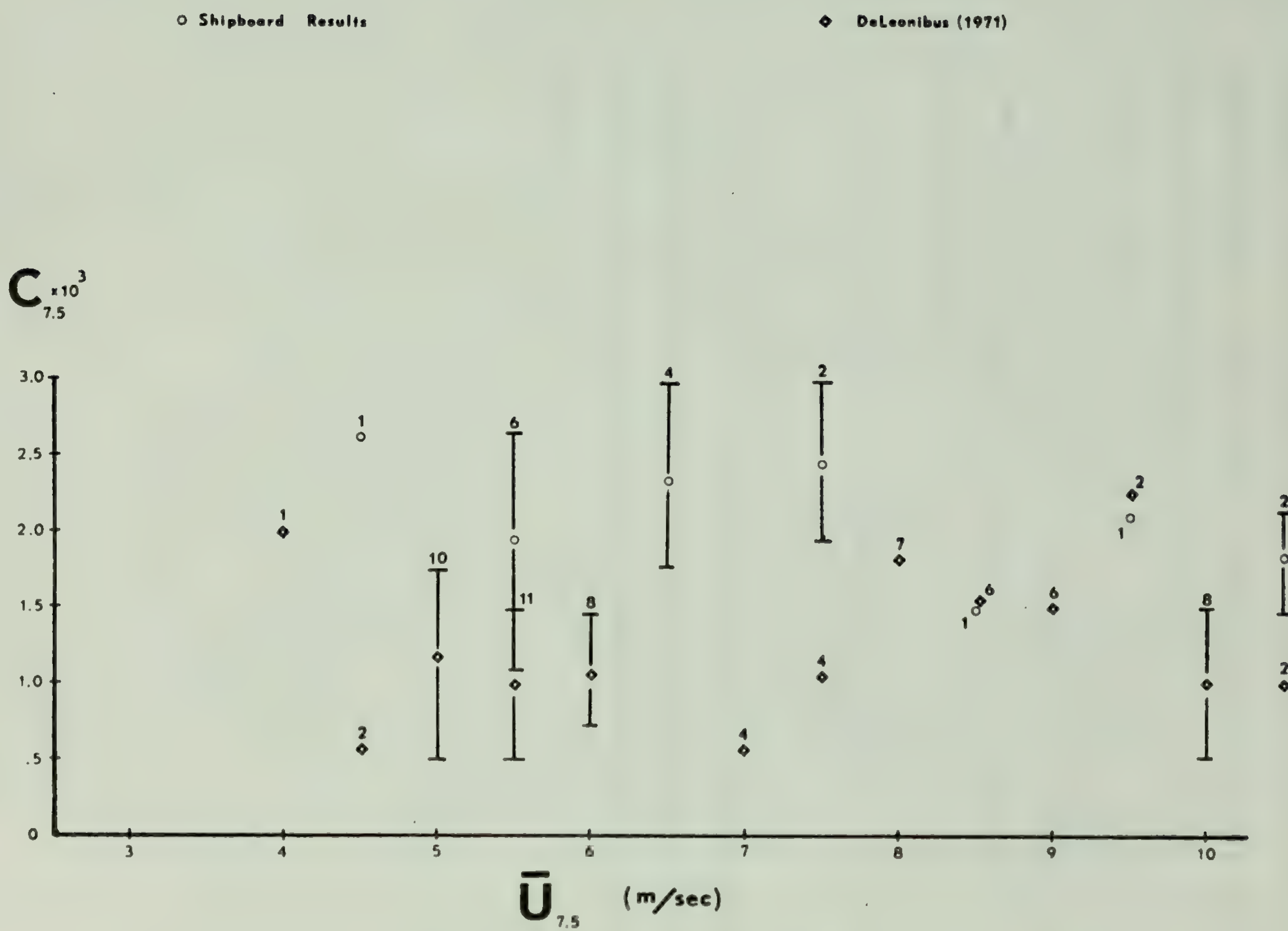
$\theta_2 - \theta_1 \equiv$ virtual potential temperature gradient

$\bar{u}_2 - \bar{u}_1 \equiv$ mean wind shear

$\bar{T} \equiv$ mean temperature for 3.9 to 14.0 meter layer.

The values at Z_1 and Z_2 were extrapolated from the profiles.

De Leonibus (1971) examined drag coefficient results for a wide range of Ri, including stable, neutral, and unstable atmospheric



o Shipboard Results
◆ DeLeonibus (1971)
C x10^3 7.5
3.0
2.5
2.0
1.5
1.0
.5
0
3
4
5
6
7
8
9
10
Ū 7.5 (m/sec)

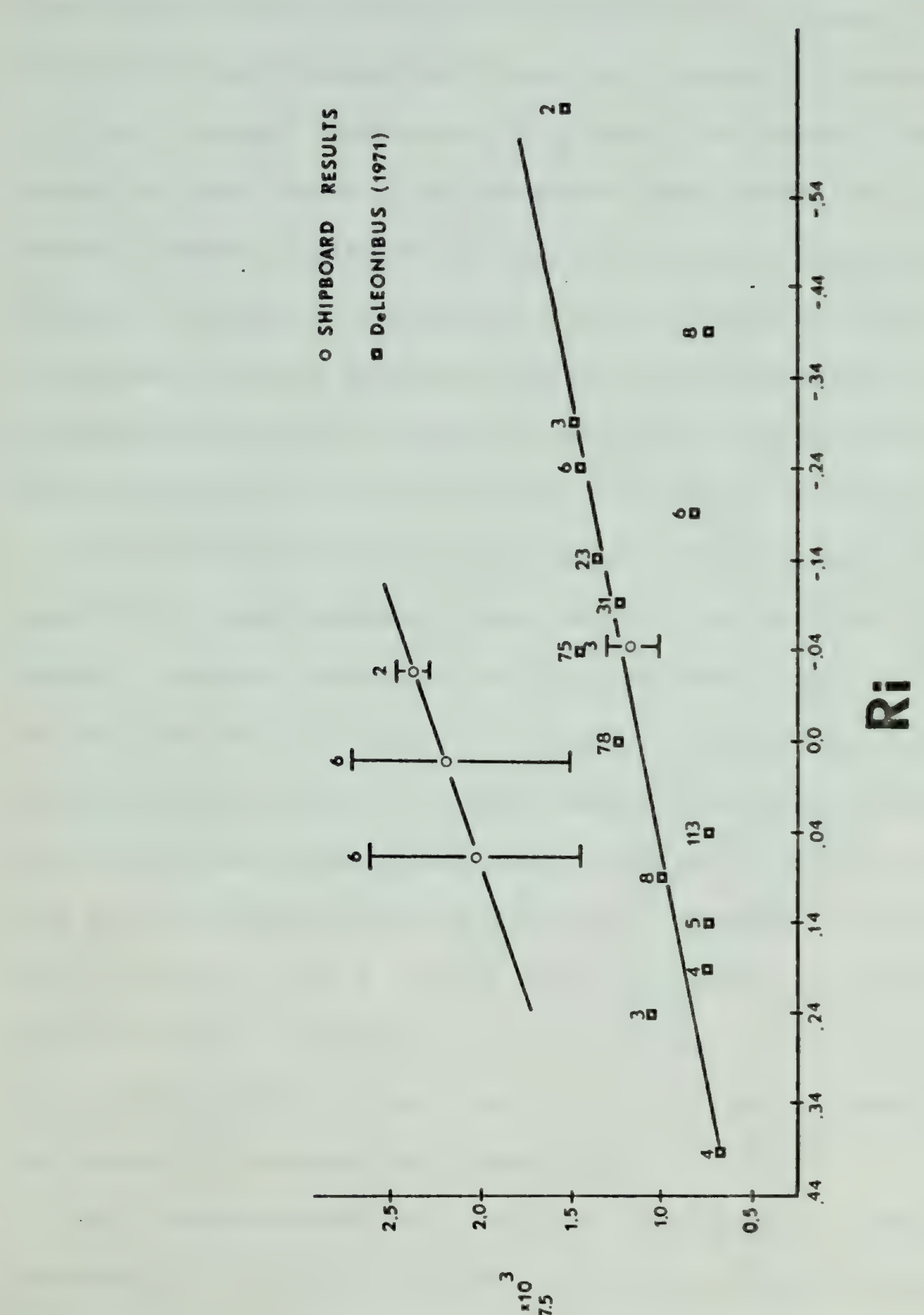
Figure 18

conditions. The Ri values obtained in this study were all in the near neutral range. In Figure 19 the shipboard results for $C_{7.5}$ are consistently about twice as high. However, the trend with respect to Ri closely parallels the trend obtained by De Leonibus. Even though the shipboard results are for a comparatively narrow range of Ri, $C_{7.5}$ is seen to definitely increase with decreasing stability.

The observed Ri dependence was expected on the basis of the defining relationship

$$C_z = \left[\frac{k}{\ell n \frac{Z}{Z_o} - \psi(Ri)} \right]^2 . \qquad (24)$$

This expression predicts that decreasing stability (and therefore increasingly smaller positive or larger negative values of Ri) reduces the denominator in the above expression and hence leads to increasing values of C_z.



o SHIPBOARD RESULTS
▫ DeLEONIBUS (1971)
$C_{7.5} \times 10^3$
Ri
2.5
2.0
1.5
1.0
0.5
.44
.34
.24
.14
.04
0.0
-.04
-.14
-.24
-.34
-.44
-.54

Figure 19

VI. CONCLUSIONS

With regard to the suitability of shipboard measurements, comparisons of the derived parameters from profiles with results from more stable platforms indicate that there is an effect on the winds due to the ship's motion. Specifically, C_z and Z_o were generally higher. This could have been caused by the sensors vertical motion through a logarithmic profile. Although the ship's motion would displace each sensor an equal distance above and below its mean height, by virtue of the logarithmic vertical profile of the property being measured, the decrease below the mean height would be dominant. This effect becomes more pronounced the closer the sensor is to the sea surface.

There are definite indications, however, that a ship is a suitable platform for some estimates. Examination of the profiles of the virtual potential temperature and the mean wind clearly showed them to be logarithmic as predicted. The values obtained for the Richardson number from shipboard profiles compared favorably with other results in some ranges of wind speed. Comparison of the shipboard and previous results, obtained from stable platforms, for the change of C_z with Ri or with $\bar{u}_z$ and the change of Z_o with u_* showed considerable agreement. It remains to be seen whether or not the definite bias introduced by the ship's motion on the Z_o and C_z values can be accounted for quantitatively (Welsh, 1974).

The instrumentation used was found to be adequate. The quartz thermometer was found to be sufficiently accurate and durable for shipboard profile measurements. The Weathermeasure Corporation IS6

motor aspirated radiation shield was apparently too fragile; two failed to function properly. On the other hand, the C. C. Breidert Company Air-X-Hauster type 6L, three of which were used during this experiment, functioned satisfactorily. The performance of the C. W. Thornthwaite cup anemometers was excellent. The only difficulty encountered was with the mechanical counter, which, when wind speeds exceeded 30 knots, did not respond properly to the electrical impulses it received from the photocell assembly. A solution would be to employ an electronic counter. This has been tried in subsequent experiments and solved the problem.

The Hygrosystems hygrometers functioned satisfactorily. They proved to be easy to use and were accurate enough for the shipboard profile measurements. Caution must be exercised, however, since exposure to large amounts of salty sea spray for any length of time will ruin them. In heavy seas the lower level hygrometers should be removed.

VII. SUGGESTIONS FOR FUTURE WORK

There are two refinements that could be made in sensor arrangement. The first would facilitate mounting and reduce by one-half the number of power cables and radiation shields. This can be accomplished simply by mounting both the temperature probes and the humidity sensors in the same aspirated radiation shield. This would assure a more uniform air flow over both sensors and correspondingly improve the results obtained. The second refinement would be to obtain a description of the profiles nearer the surface. This could be accomplished by using a spar buoy with a sea anchor and two sets of sensor arrays. Deployed upwind of the anchorage site, these sensors would be free from the effect of the ship's superstructure and motion and could yield valuable near surface information regarding the turbulent and mean structure of the atmosphere over ocean waves. It is suspected that the influence of the waves would be most evident in near surface data.

APPENDIX A

THE DATA

1. Mean Wind Velocity

The wind speeds are listed in centimeters per second rounded to the nearest hundredth, and are an average for the ten-minute period beginning at the time indicated. For almost four hours, commencing at 2015, 20 September, the counter for the middle level did not advance properly. The problem was rectified by midnight.

DATE	TIME	4.5 METERS	8.4 METERS	13.2 METERS
20 September 1973	0945	567.74	697.44	644.72
	0955	576.41	627.87	647.85
	1005	579.50	612.27	627.60
	1015	584.59	644.72	688.71
	1025	531.71	725.28	684.64
	1035	603.82	573.28	598.54
	1045	507.57	553.84	584.82
	1055	430.59	495.28	516.29
	1105	454.06	487.94	520.62
	1115	413.38	442.79	467.83
	1125	406.99	441.32	466.08
	1135	401.08	432.51	461.17
	2015	811.11	*	1047.24
	2025	872.40	*	1013.08
	2035	914.82	*	1037.36
	2045	792.24	*	928.95
	2055	855.86	*	975.62
	2105	898.55	*	1055.24
	2115	1002.00	*	1174.73
	2125	994.31	*	1104.50
	2320	962.39	*	1133.07
	2330	940.97	*	1068.20
	2340	793.14	*	900.03
	2350	781.69	*	871.95
21 September 1973	0000	696.62	741.37	784.24
	0010	579.50	637.93	668.95
	0020	573.55	618.70	661.26
	0030	687.01	739.94	792.24
	0040	636.27	675.70	692.06

TIME	4.5 METERS	8.4 METERS	13.2 METERS
0625	471.98	511.23	570.15
0635	489.15	532.87	558.13
0645	506.36	567.74	596.62
0655	525.67	539.13	561.53
0705	508.78	542.97	561.75
0715	503.90	542.30	554.69
0725	513.65	549.95	562.47
0735	554.55	590.81	634.84
0745	507.79	565.60	576.91
0945	517.05	595.42	669.96
0955	544.71	609.42	626.67
1005	538.91	583.90	618.80
1015	497.76	536.55	569.90
1025	570.64	601.67	625.95

2. Mean Temperature

The mean temperatures are listed in degrees centigrade rounded to the nearest hundredth. The calibration correction factor has been entered. The quartz thermometer is an integrating device; the temperatures listed are from one-second integrations. The times chosen to make temperature readings are the centers of the ten-minute periods over which the mean wind was computed.

20 September 1973	TIME	SEA SURFACE	3.9 METERS	7.7 METERS	12.7 METERS	14.0 METERS
	0950	14.74	15.26	15.89	15.73	15.28
	1000	14.74	15.25	16.00	15.87	15.29
	1010	14.74	15.47	16.10	15.91	15.46
	1020	14.74	15.54	16.02	15.79	15.49
	1030	14.74	15.83	15.44	15.55	15.52
	1040	14.76	15.63	16.02	15.86	15.47
	1050	14.78	15.53	16.06	15.93	15.44
	1100	14.80	15.46	16.17	16.21	15.43
	1110	14.83	15.46	16.53	16.29	15.47
	1120	14.84	15.59	16.37	16.51	15.57
	1130	14.89	15.61	16.53	16.62	15.59
	1140	14.90	15.70	16.75	16.89	15.80
	2010	15.05	16.12	16.65	16.39	16.20
	2020	15.03	16.02	16.65	16.41	16.21
	2030	15.04	16.13	16.64	16.45	16.24
	2040	15.03	16.12	17.01	16.52	16.20
	2050	15.03	16.01	16.60	16.37	16.11

	TIME	SEA SURFACE	3.9 METERS	7.7 METERS	12.7 METERS	14.0 METERS
	2100	15.03	16.06	16.96	16.50	16.14
	2110	15.03	16.02	16.84	16.39	16.08
	2120	15.02	15.96	16.12	15.98	15.92
	2130	15.00	15.85	15.96	15.79	15.75
	2140	14.98	15.73	15.99	15.67	15.73
	2315	15.02	15.47	15.82	15.53	15.41
	2325	15.00	15.49	15.92	15.56	15.44
	2335	15.01	15.56	15.67	15.48	15.45
	2345	15.03	15.46	16.25	15.69	15.35
	2355	15.01	15.42	15.92	15.56	15.31
21 September 1973	0005	15.04	15.37	15.75	15.57	15.28
	0015	15.04	15.29	15.97	15.72	15.22
	0025	15.03	15.19	15.93	15.71	15.12
	0035	15.04	15.24	15.64	15.44	15.18
	0045	15.05	15.20	15.91	15.70	15.14
	0630	14.84	14.82	15.73	15.65	14.73
	0640	14.89	14.82	15.67	15.61	14.76
	0650	14.93	14.83	15.68	15.56	14.79
	0700	15.00	14.85	15.90	15.79	14.79
	0710	15.00	14.88	15.75	15.69	14.84
	0720	15.00	14.97	15.92	15.83	14.94
	0730	14.99	14.97	15.78	15.74	14.96
	0740	15.00	15.10	15.77	15.59	15.08
	0750	15.01	15.08	15.74	15.71	15.08

3. Mean Relative Humidity

The relative humidity readings are listed to the nearest tenth of a percent. The relative humidity data were taken at the same time as the quartz thermometer temperature observations were made.

20 September 1973	TIME	3.9 METERS	7.7 METERS	14.0 METERS
	0950	91.3	93.4	88.3
	1000	91.0	93.1	89.6
	1010	91.0	93.1	90.2
	1020	89.4	90.9	88.5
	1030	89.7	91.1	88.3
	1040	89.6	90.2	88.2
	1050	83.4	84.0	82.9
	1100	89.1	89.6	88.9
	1110	89.5	89.3	89.5
	1120	88.3	88.8	88.8
	1130	89.2	90.0	90.3
	1140	88.4	89.0	89.8

	TIME	3.9 METERS	7.7 METERS	14.0 METERS
	2010	98.6	92.2	84.5
	2020	99.1	92.2	84.1
	2030	98.7	91.1	82.8
	2040	99.1	90.8	82.6
	2050	99.3	90.6	82.8
	2100	99.1	90.2	83.3
	2110	98.7	90.0	82.7
	2120	99.2	90.8	83.0
	2130	98.7	90.7	82.5
	2140	99.0	91.1	82.2
	2315	99.1	92.3	85.4
	2325	99.0	92.0	85.0
	2335	99.0	91.5	83.9
	2345	99.4	92.2	84.7
	2355	99.1	91.6	85.0
21 September 1973	0005	99.1	91.6	86.3
	0015	99.1	92.0	87.3
	0025	99.0	91.9	87.6
	0035	99.6	92.2	88.1
	0045	99.3	92.0	88.0
	0630	98.7	91.1	88.0
	0640	98.5	91.1	88.0
	0650	98.0	90.8	87.6
	0700	98.1	91.2	88.1
	0710	98.4	91.1	88.0
	0720	98.4	90.7	87.0
	0730	97.3	89.4	86.9
	0740	97.7	88.6	86.7
	0750	98.4	88.2	86.3

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C
C
C
C                          APPENDIX B
C
C
C
C      SAMPLE PROGRAM CF COMPUTATIONS FOR THE VIRTUAL
C                   POTENTIAL TEMPERATURE
C
C
C
C
C      THIS PROGRAM TAKES THE INPUTS MEAN TEMPERATURE,
C      MEAN RELATIVE HUMIDITY, AND PRESSURE AND FROM
C      THEM COMPUTES THE VIRTUAL POTENTIAL TEMPERATURE.
C
      DIMENSICN Y(5),HEIGHT(5),R1(5),T1(5),THETA(5),TV(5),
     1T10630(5),T10640(5),T10650(5),T10700(5),T10710(5),
     2T10720(5),T10730(5),T10740(5),T10750(5),R10630(5),
     3R10640(5),R10650(5),R10700(5),R10710(5),R1C72075),
     4R10730(5),R10740(5),R10750(5)
C
C      THE FOLLOWING SERIES OF STATEMENTS READS IN THE
C      TEMPERATURE AND RELATIVE HUMIDITY VALUES FOR 21
C      SEPTEMBER 1973, 0630 TO 0750. SIMILAR STATEMENTS
C      WERE EMPLOYED FOR THE OTHER TIME PERICDS CF THIS
C      EXPERIMENT.
C
      READ(5,1000)(T10630(I),I=1,5)
      READ(5,1000)(T10640(I),I=1,5)
      READ(5,1000)(T10650(I),I=1,5)
      READ(5,1000)(T10700(I),I=1,5)
      READ(5,1000)(T10710(I),I=1,5)
      READ(5,1000)(T10720(I),I=1,5)
      READ(5,1000)(T10730(I),I=1,5)
      READ(5,1000)(T10740(I),I=1,5)
      READ(5,1000)(T10750(I),I=1,5)
      READ(5,1000)(R10630(I),I=1,5)
      READ(5,1000)(R10640(I),I=1,5)
      READ(5,1000)(R10650(I),I=1,5)
      READ(5,1000)(R10700(I),I=1,5)
      READ(5,1000)(R10710(I),I=1,5)
      READ(5,1000)(R10720(I),I=1,5)
      READ(5,1000)(R10730(I),I=1,5)
      READ(5,1000)(R10740(I),I=1,5)
      READ(5,1000)(R10750(I),I=1,5)
      WRITE(6,4000)
      PRESS=1015.
C
C
C      THE MEAN ATMOSPHERIC PRESSURE FCR THIS TIME PERICD
C      WAS 1015 MB.
C
C      THE FIVE HEIGHTS FOR WHICH THE TEMPERATURE AND
C      RELATIVE HUMIDITY WERE KNOWN ARE 10, 389, 770,
C      1273, AND 1397 CENTIMETERS.  BELOW ARE THE LOG
C      BASE 10 CF EACH OF THESE HEIGHTS.
C
      Y(1)=1.
      Y(2)=2.58952
      Y(3)=2.88628
      Y(4)=3.0466
      Y(5)=3.4520
C
C      HEIGHTS IN CENTIMETERS
C
      HEIGHT(1)=10.
      HEIGHT(2)=388.62
      HEIGHT(3)=769.62
      HEIGHT(4)=1272.54
```

```
      HEIGHT(5)=1397.
C
C         NOW INITIALIZE THE COUNTERS KOUNT AND MC.
C
      KOUNT=2
      MC=1
 111  IF(KOUNT.GT.2)GO TO 1
      DO 100 I=1,5
      T1(I)=T10630(I)+273.16
      R1(I)=R10630(I)/100.
 100  CONTINUE
      GO TO 666
 1    IF(KOUNT.GT.3)GO TO 2
      DO 101 I=1,5
      T1(I)=T10640(I)+273.16
      R1(I)=R10640(I)/100.
 101  CONTINUE
      GO TO 666
 2    IF(KOUNT.GT.4)GO TO 3
      DO 102 I=1,5
      T1(I)=T10650(I)+273.16
      R1(I)=R10650(I)/100.
 102  CONTINUE
      GO TO 666
 3    IF(KOUNT.GT.5)GO TO 4
      DO 103 I=1,5
      T1(I)=T10700(I)+273.16
      R1(I)=R10700(I)/100.
 103  CONTINUE
      GO TO 666
 4    IF(KOUNT.GT.6)GO TO 5
      DO 104 I=1,5
      T1(I)=T10710(I)+273.16
      R1(I)=R10710(I)/100.
 104  CONTINUE
      GO TO 666
 5    IF(KOUNT.GT.7)GO TO 6
      DO 105 I=1,5
      T1(I)=T10720(I)+273.16
      R1(I)=R10720(I)/100.
 105  CONTINUE
      GO TO 666
 6    IF(KOUNT.GT.8)GO TO 7
      DO 106 I=1,5
      T1(I)=T10730(I)+273.16
      R1(I)=R10730(I)/100.
 106  CONTINUE
      GO TO 666
 7    IF(KOUNT.GT.9)GO TO 8
      DO 107 I=1,5
      T1(I)=T10740(I)+273.16
      R1(I)=R10740(I)/100.
 107  CONTINUE
      GO TO 666
 8    IF(KOUNT.GT.10)GO TO 9
      DO 108 I=1,5
      T1(I)=T10750(I)+273.16
      R1(I)=R10750(I)/100.
 108  CONTINUE
 666  KOUNT=KOUNT+1
C
C         THE FOLLOWING SERIES OF FORTRAN STATEMENTS WERE
C         DEVELOPED FROM HESS(1959) INTEGRATION OF THE
C         CLASIUS CLAPEYRON EQUATION TV(I) IS THE ARRAY THAT
C         CONTAINS THE VIRTUAL TEMPERATURE AND THETA(I)
C         HOLDS THE VIRTUAL POTENTIAL TEMPERATURE.
C
      DO 200 I=1,5
      T=(1./273.)-(1./T1(I))
      Z=5419.*T
      ES=6.11*EXP(Z)
      E=ES*R1(I)
```

```
      CCNST=E/PRESS
      TV(I)=(1.+CONST)*T1(I)/(1.+.622*CCNST)
      THETA(I)=TV(I)+.000098*HEIGHT(I)
200   CONTINUE
9     IF(KOUNT.EQ.11)GO TO 9999
      WRITE(6,3000) (THETA(I),I=1,5)
1000  FORMAT(5F10.6)
2000  FORMAT(6A8)
3000  FORMAT(' ',5F11.4)
4000  FORMAT(' ',2X,'LEVEL 1',4X,'LEVEL 2',4X,'LEVEL 3',4X,'
     1LEVEL 4',4X,'LEVEL 5')
      GO TO 111
9999  STOP
      END
```

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The suitability of shipboard profile measurements of mean temperature, mean humidity and mean wind over the open ocean is examined on the basis of six hours and 20 minutes of simultaneous profile measurements made from the R/V Acania on 20-21 September 1973 near San Nicolas Island, California. Comparisons of the profiles obtained from the shipboard measurements, as well as the meteorological parameters derived from those profiles are made with results obtained from more stable platforms. Parameters examined include

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the Richardson number, the friction velocity, the drag coefficient and the roughness length.

The drag coefficient and roughness length were found to be generally larger than those obtained from more stable platforms, but the Richardson number and the relationships between the various parameters, as well as the profiles of wind speed and temperature themselves, compare favorably. The results indicate that a ship can be a suitable platform for measuring profiles.

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